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DRIFT OF SUBMERGED OIL AT SEA

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SUMMARY/ SAMMENDRAG

The report presents results from a major study concerning dispersion of oil from a drifting slick at sea. The major emphasis is given to a discussion of the mechanisms governing the rate of dissipation of oil from the slick. By combining theoretical analysis and available observations from real oil spills, a model has been developed which reproduces the main aspects of the process of natural dispersion. The results have been used to evaluate the possibility of shore stranding of oil drifting subsea.

KEY WORDS/ STIKKORD

OIL SLICK	SEA-STATE
BREAKING WAVE	DISPERSION

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Skipnes Offsettrykkeri A/S

PREFACE

The present report is intended to serve two purposes. Primarily, it sums up the results at the present stage of a study of the mechanisms of dispersion of oil. This study, which has been in progress for about a year is founded by EXXON ("Dispersion Mechanisms and Rates of Chemically Treated and Untreated Oil spills"), FOH (Project 111) and IKU. The aim of the study has been to obtain an improved concept for handling the process of dissipation of oil from a drifting oil slick in the context of an existing model for drift and spreading of oil at the sea. Secondly, as a result of a request from the Norwegian State Pollution Board (SFT), the risk for shore pollution due to drift of submerged oil has been considered. The last problem has strengthend the need for quantitative results as opposed to a pure explanatory approach. This has required special efforts related to quantitative estimation of the various parameters involved, which has been a rather comprehensive task in a field of research where both empirical experience and theoretical knowledge are deficient. However, as a result of a number of assumptions and simplifications, it has been possible to obtain relations between the various parameters and the seastate. Additional parameters such as the size distribution of the oil particles mixed into the sea from an oil slick have been established on the basis of available observations from real oil spills. In total, this has led to a model for the dispersion of oil which, in the view of the author, reproduces the most important physical aspects of the process. As such, the model may be seen as a promising first step towards an improved large scale oil drift model.

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DRIFT OF SUBMERGED OIL AT SEA

1. INTRODUCTION

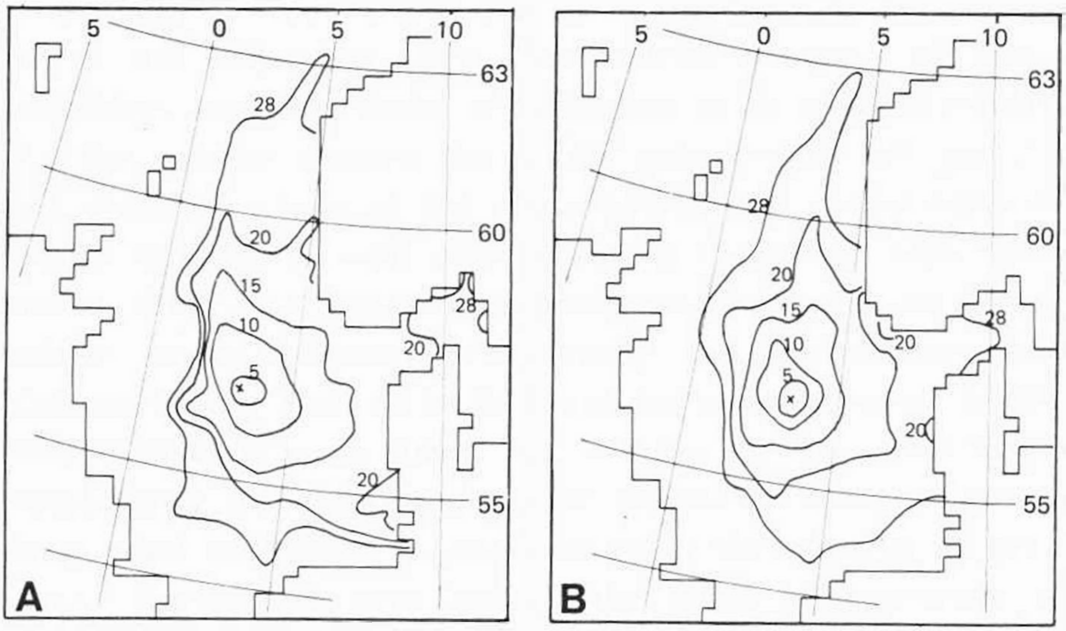
It is well known that a drifting oil slick will release oil to the underlying water masses in a rate depending upon the sea conditions. The drift of this submerged oil will in general deviate from the drift of the surface oil, and may thus cause shore pollution at sites where no surface oil has been observed. Occations of stranded oil at the western coast of Sweden have been postulated to be caused by such submerged oil emanating from oil production platforms in the North Sea. One of the aims of this report is to evaluate the validity of this assumption. In order to do this several aspects of oil drift and weathering have to be taken into account, including both surface drift, evaporation and dissipation of the surface oil and the behaviour of submerged oil. While the drift and weathering of surface oil is rather well explained, the knowledge of the behaviour of dispersed oil is rather limited. However, some progress has been made during the recent years with respect to the understanding of the mechanisms governing the mixing processes and the residence time of submerged oil in the sea. A rather detailed discussion on these achievements will be given later in this report.

The spreading of submerged oil will be closely linked to the drift and weathering of the oil on the surface. The dissipation of oil into the sea is a continuous process, and each position of the surface oil may be seen as an origin for a trajetory of a submerged oil volume. The volume of oil submerged is, however, depending upon the amount of oil at the surface, which is reduced by time due to the effect of weathering and dissipation. In total, this indicates that the area where subsurface drift may be originated is not limited to the site of the spill. On the other hand it puts some constraints on the area where subsurface oil of any importance may be released. Adding to this picture the limits with respect to residence time of submerged oil, one may at the end be able to judge the validity of the assumption presented in the introduction.

2. DRIFT AND WEATHERING OF SURFACE OIL

Experiments with drifting cards and bottles are the main source of information on the surface drift in the North Sea. By assuming a certain wind drift factor, such information has made it possible to establish a residual current field (Dons 1977). By superposition of this residual current field and wind drift from historical wind data, it is possible to compute long term statistics for the drift and spreading of surface oil from a given spill site. Such computations have been published by both IKU (Audunson et al 1978) and NMI (Haug and Jensen 1978) for several spill sites, including Ekofisk, which is of major interest in this report.

In addition to the surface drift, both evaporation and dissipation of the oil into the sea have been taken into account in the computations. The basis for the evaluation of these weathering effects is different in the two studies, with both effects included in a single seastate-dependent loss factor by NMI, while the IKU-study handles the two effects separately.



WINTER SEASON

SUMMER SEASON

Fig. 1 Average drift time (days) of oil released from Ekofisk in the winter season (A), and the summer season (B). After Haug and Jensen (1978).

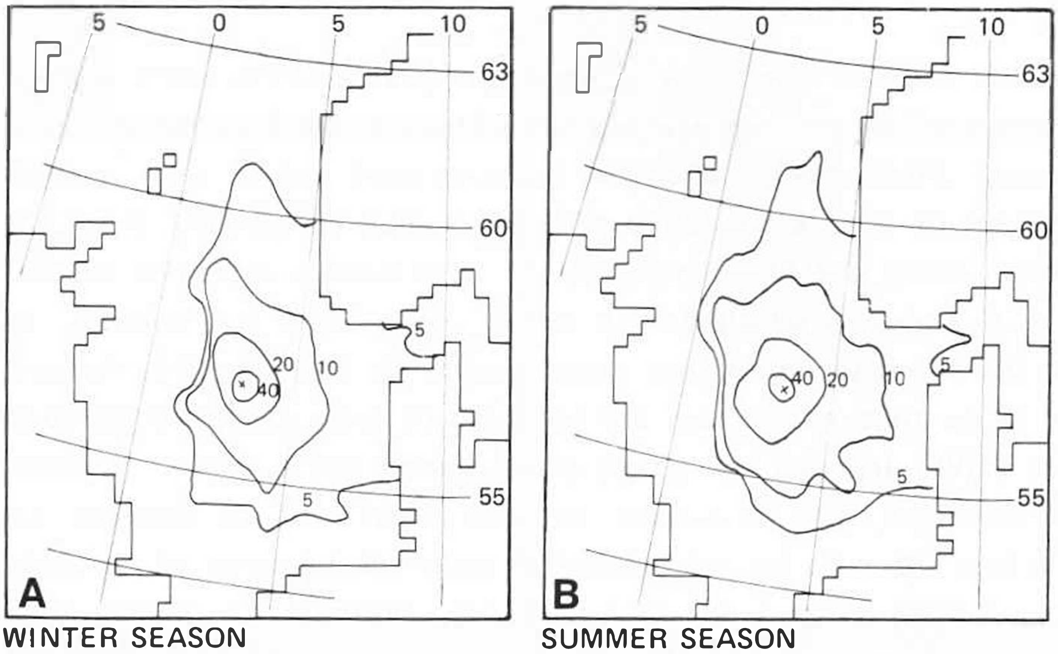


Fig. 2 Drifting oil volumes in percentage of daily spill at Ekofisk (After Haug and Jensen 1978).

The model derived by IKU also takes into account the composition of the oil in the evaporation term. Thus, from the point of view of physical modelling, the IKU results are expected to be the most reliable. However, for the present purpose the results published by NMI are chosen due to the illustrative form of the presentation. The computations are based on nearly 5 years of wind data, covering the period from October 1972 to March 1977. The results are presented separately for the summer and winter season, covering respectively the months April-September and October-March. Each oil lot is traced for a period limited to 28 days or the time it takes to reach shore. Fig. 1 shows the mean drift time obtained for respectively the winter and summer season. As seen, the time to reach the west coast of Sweden is found to be in the order of or greater than 28 days. During this drift period, the effect of weathering will strongly reduce the amount of oil at the surface. This is shown in fig. 2 where the contours indicates the reduction in percent of the original diurnal oil lots due to evaporation and dissipation.

Results from drifting card experiments performed in 1972 indicates a drift period between 1 and 2 months for cards stranding at the western coast of Sweden after having been dropped at Ekofisk (Dons 1977). Computations of the drift trajectories based on wind drift and a best fit residual current pattern indicates a slow drift in the main North Sea basin, while the drift is speeded up appreciably when the trajectory enters the Skagerak. Typical drift periods for these cases are in the order of 30 days before entering Skagerak, and 10 days for the rest of the drift up to the western coast of Sweden. The computations performed by IKU (1978) also includes an example of the same kind of situation. Fig. 3 shows the results obtained in terms of the area influenced by oil after the end of a 30 days spill period. In addition, the status of the further drift is shown up to the time when all the oil lots have stranded or dissipated into the sea.

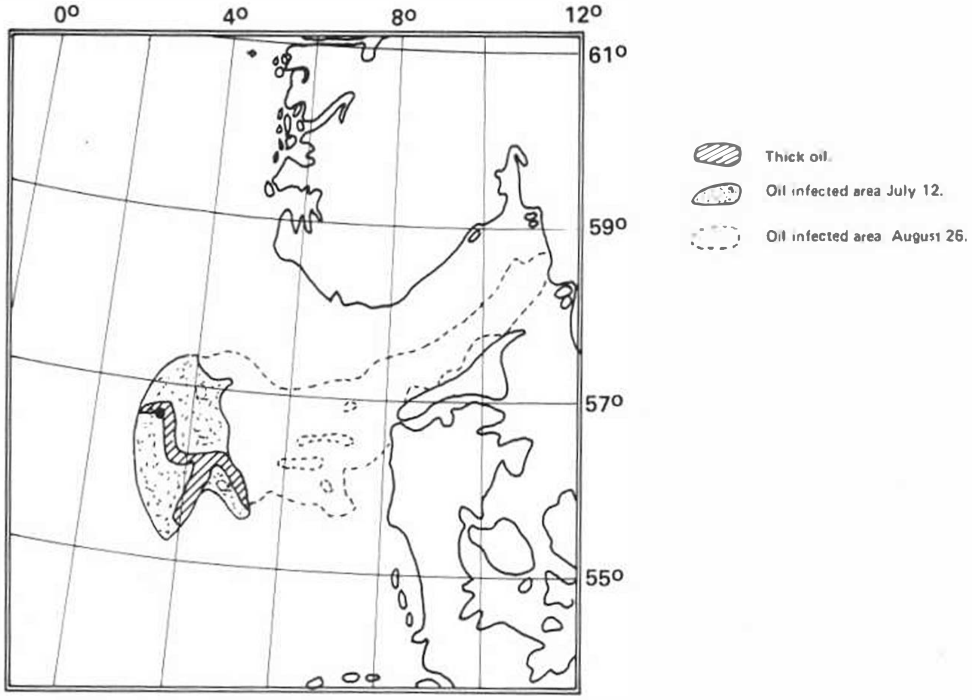


Fig. 3. Computations of drift and spreading of surface oil from Ekofisk. The spill is assumed to last for a 30 days period, starting at June 12. After Audunson et al (1978).

The previous review indicates that an oil spill released at Ekofisk may reach the shore at the western coast of Sweden. However, rather long drifting periods may be expected, with typical values ranging from one to two months.

The computations presented indicate a rather slow drift within the main North Sea basin, and a correspondingly strong reduction of the diurnal oil lots due to weathering effects in this area. By entering the Skagerak, the surface oil has been found to be reduced to 5 percent due to evaporation and dissipation. In the Skagerak, the surface drift is found to increase considerably, with typical drift periods at 10 days for this part of the trajectories. In total, the surface drift is found to be governed mainly by wind drift in the central North Sea, while the coastal current north of Denmark plays an important role in the Skagerak.

3. MIXING OF OIL INTO THE WATER MASSES

In the previous chapter, the term dissipation has been used to describe the loss of oil from the surface to the underlying water masses. In recent years this mechanism has been studied both experimentally and theoretically, and it seems to be a general agreement that the action of breaking waves is the main factor causing this loss. The breaking waves splits the surface oil into droplets, which are mixed rather instantaneously into the water masses. The further motion of these droplets is then seen to be governed by a balance of the buoyance of the oil droplets and the downward mixing effect cause by the turbulence in the water masses. The major parameters governing this process are the terminal velocity of the particles, the level of turbulence and the initial mixing depth.

a) Terminal velocity and particle size.

The terminal velocity of a rising droplet in water equals the velocity under steady state conditions where the gravity force exactly balances the resistance:

$$\frac{\pi d^3}{6} \Delta\rho g = C_D \frac{\pi d^2}{4} \frac{w^2 \rho}{2}$$

where d is the particle diameter

$\Delta\rho$, the density difference between water and droplet fluid

w, the particle velocity

ρ, density of water

C_D, drag coefficient

The drag coefficient is in general found to be related to the Reynolds number Re:

$C_D = f(Re)$,

$Re = w\rho d/\mu$

where μ is the dynamic viscosity of water.

The standard relationship obtained for fixed spheres is shown at fig. 4. Two distinct regions may be seen. At small Reynolds numbers, $Re < 1$, a linear relationship is established where

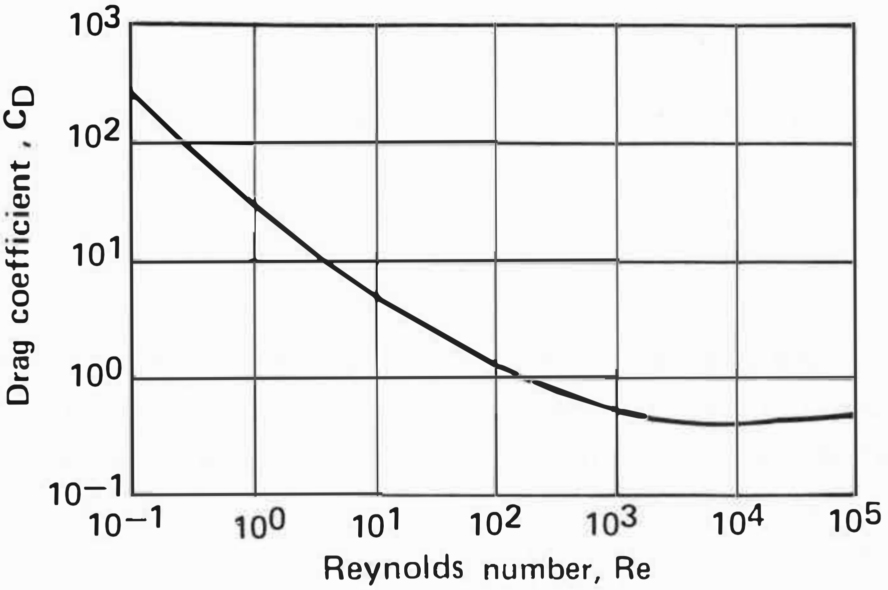


Fig. 4. Standard relationship $C_D = f(Re)$ for fixed spheres (Yalin 1972).

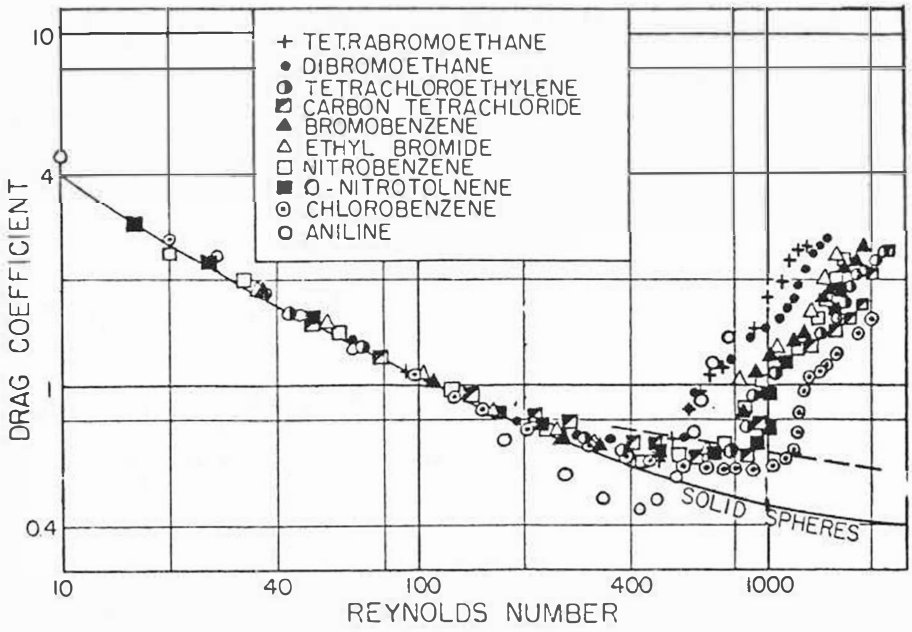


Fig. 5. Drag coefficient versus Reynolds number. Experimental results for free falling liquid drops in water. After Hu and Kinter (1955)

$$C_D = 24/Re, \quad Re \leq 1$$

At large Reynolds numbers, C_D is found to be constant:

$$C_D = 0.4, \quad Re > 1000$$

However, as shown by Hu and Kintner (1955) and Boillat and Graf (1981), deviations from this standard relationship are observed both for free falling spheres and droplets. The experimental results for droplets given at fig. 5 shows a fairly good agreement with the standard curve at Reynolds numbers below 300. As the Reynolds number increases from this value, the C_D value starts to depart from the standard curve. When Re reaches a certain value, C_D starts to increase rather abruptly. Observations of the droplet motions indicates that the first departure from the standard curve corresponds to an oscillatory motion of the droplets. Similiar observations are reported for solid spheres. The rather abrubt rise in C_D at still higher Reynolds numbers are related to an increasing deformation of the droplets, ultimately leading to a splitting of the droplet.

The terminal velocity of droplets at this range of Reynolds numbers is found to have a peak value, followed by a slight decrease at increasing values of Re. The peak terminal velocity is found to depend on the interfacial tension in addition to the other physical properties of the system (Hu and Kintner 1955):

$$(Re)_P = 2.92\, P^{0.238}$$

where $P = \sigma_i^3 \rho^2 / g \Delta\rho \mu^4$
σ_i, the interfacial tension

The dimensionless number P is a physical property group defined by Hu and Kintner.

Fig. 6 shows computed values of the terminal velocity of oil droplets of various size based on the empirical relation derived by Hu and Kintner. For comparison, some results reported for free falling solid spheres by

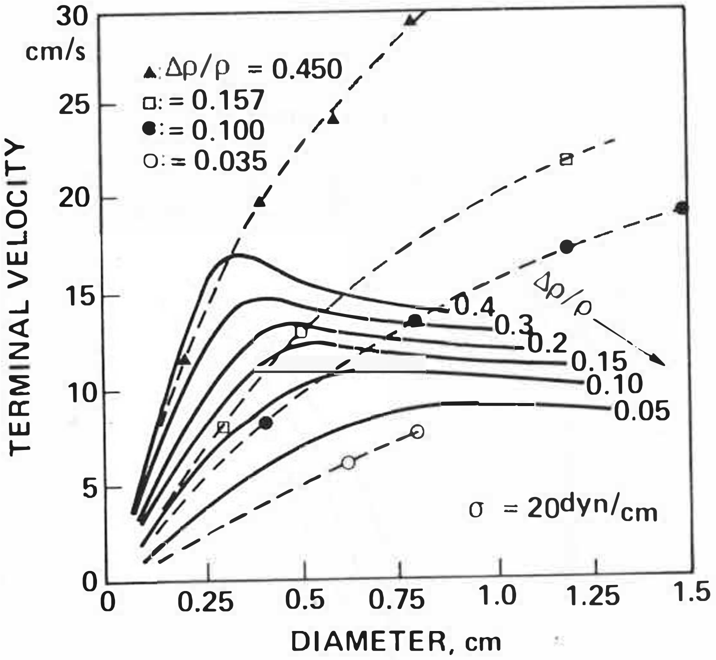


Fig. 6. Terminal velocity of droplets according to Hu and Kintner (1955), (solid lines), compared to observations for free falling solid spheres by Boillat and Graph (1981), (dashed lines).

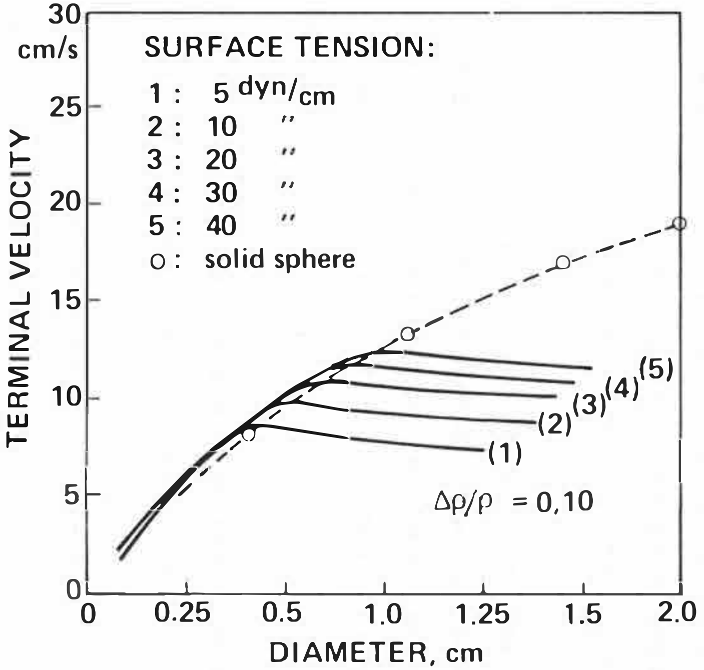


Fig. 7. The influence of surface tension on the terminal velocity of droplets. Solid lines according to Hu and Kintner (1955) Data for free falling spheres from Boillat and Graph (1981)

Boillat and Grat is included at the same figure. The terminal velocity of the droplets is found to level out at a certain point, while the velocity of the solid spheres is found to increase approximately with the square root of the particle size, as predicted by the C_D = constant relation.

The influence of the surface tension on the terminal velocity is shown at fig. 7. Also here, experimental data for solid spheres are included. The fact that droplets with high surface tension behaves more like solid spheres seems to confirm the assumption regarding the effect of droplet deformation.

Observations of oil on the sea from real and experimental oil spills indicate that weathered oil may behave more like solid particles than droplets. This is due to both the loss of light oil fractions by evaporation, ultimately leaving a rather stiff substance (tar balls) as the final residue, and the forming of highly viscous water in oil emultion (chocolate mousse). Unfortunately the influence of the viscosity of the droplet fluid is not included in the empirical correlations derived by Hu and Kintner. In order to take into account this weathering effect, one might, however, introduce an artificial high value of the surface tension, which makes the predicted terminal velocity to correspond to the solid particle case.

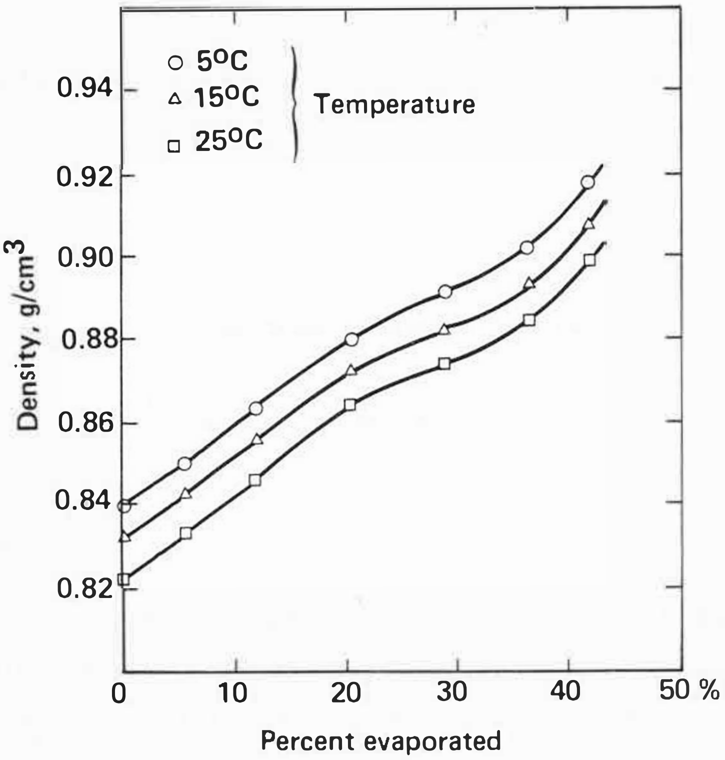


Fig. 8. Density of crude oil at various stages of weathering.
Mackay and Leinonen (1977).

The effect of weathering on the density of crude oil is illustrated at fig. 8, based on data reported by Mackay et al. (1977). The figure indicates and increase in density from about 0.84 g/cm^3 to 0.92 g/cm^2 due to evaporation. The uptake of water in the oil has been observed to be ranging from 50 to 70% in stable water in oil emultions. This effect will increase the density further up to approximately 1 g/cm^3.

The size distribution of droplets formed under breaking waves is known to depend on both the properties of the oil and the intensity of turbulence in the breaking wave. The deformation and splitting of droplets in turbulent flow is governed by the relative strength of the external forces to the interfacial-tension forces, as expressed by the Weber number:

$$We = \rho\, v_d^2\, d/\sigma$$

where
ρ is the density of the water,
v_d^2, the average velocity fluctuations over a distance d,
d, the droplet size
σ, interfacial tension.

The splitting of the droplets is found to occure above a certain critical Weber number. In general, this critical value is assumed to be in the order of 1. However, Hinze (1955) also shows that the value depends on the viscosity of the dispersed phase, as expressed by a dimensionless viscosity group V_i:

$$V_i = \mu_o/\sqrt{\rho_o \sigma d}$$

where μ_o and ρ_o represents the viscosity and density of the oil.

The effect of V_i on the critical Weber number may be expressed as

$$(We)_c = 1 + V_i$$

Milgram (1978) has derived an order of magnitude expression for the velocity fluctuation in wave breaking, which relates $v_d{}^2$ to the peak frequency ω_p in the frequency spectrum, and the distance equal to d:

$$v_d^2 = C_1(\varepsilon d)^{2/3}, \ \varepsilon \sim 10 \cdot g^2/\omega_p$$

where ε is the specific dissipation rate.
ω_p, the peak frequency, $2\pi/T_p$.

Milgram derived a value of 7 for the constant C_1, while Hinze (1955) proposed a value equal to 2 for the same constant of proportionality. From the above expressions, the critical diameter d_{max}, below which no splitting will occure, has been calculated for a range of interfacial tensions and viscosities. The value of ω_p is chosen equal to 2 s^{-1}, which is proposed as a typical full scale value by Milgram. The constant C_1 is also chosen in accordance with Milgram.

The results presented at fig. 9 illustrates the strong effect of a reduction in the surface tension, eventually caused by the application of a chemical dispersant. Normally, the interfacial tension of oil water is in the order of 30 dyn/cm (Milgram 1978). By adding a chemical dispersant, this may be reduced by a factor between 10 and 100. The corresponding reduction of the critical diameter will be in the order of 4 to 10.

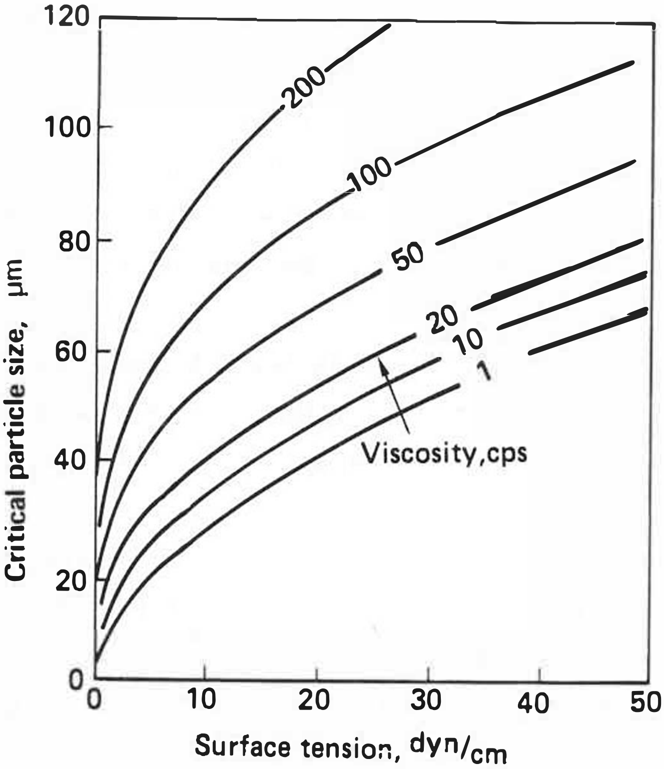


Fig. 9. Critical particle size with respect to splitting of particles in breaking waves.

It is also interesting to note the effect of viscosity on the critical diameter. Normal values of the viscosity seems to be in the order of 20 cPs (Milgram 1978). An tenfold increase to 200 cPs will produce a doubling in the critical diameter. As an effect of formation of water in oil emultions, the viscosity is known to increase by several orders of magnitude. The present analysis can not be expected to be valid for such cases, but may at least indicate that the oil droplets formed under such conditions will be appreciably larger than for fresh oil.

The critical droplet diameter derived in the previous analysis may give some indications of the particle size formed under a breaking wave. However, since the time scale of the wave breaking is small, an appreciable volume of the dispersed oil may be expected to be in the size range greater than this diameter. A large number of particles below this size will also be present, since a particle which is splitted may produce a random number of particles and not only two, which the term splitting may indicate.

Data on the size-distribution of suspended oil particles are limited, but some indications are given in a study reported by Forrester (1971). In the survey which followed the grounding of the tanker Arrow, oil particles were detected at depths down to 80 meters. From the total number of samplings, Forrester concluded that the particle sizes were evenly distributed in terms of volume in the range from 10 to 1000 microns. However, with increasing depth, the larger particles (in the range from 0.1 to 1 mm) were observed to decrease in concentration, while the concentration of the smaller particles seemed to be rather constant with depth.

Fig. 10 illustrates the variation to be expected in the terminal velocity of oil droplets within this range of particle size. The density of oil is chosen corresponding to various stages of weathering.

Forrester makes an attempt to relate the observed particle size distribution to the process of breaking up of larger oil particles into smaller ones by the action of turbulence. While this process may be of large importance in producing the particle distribution immediately after a breaking wave

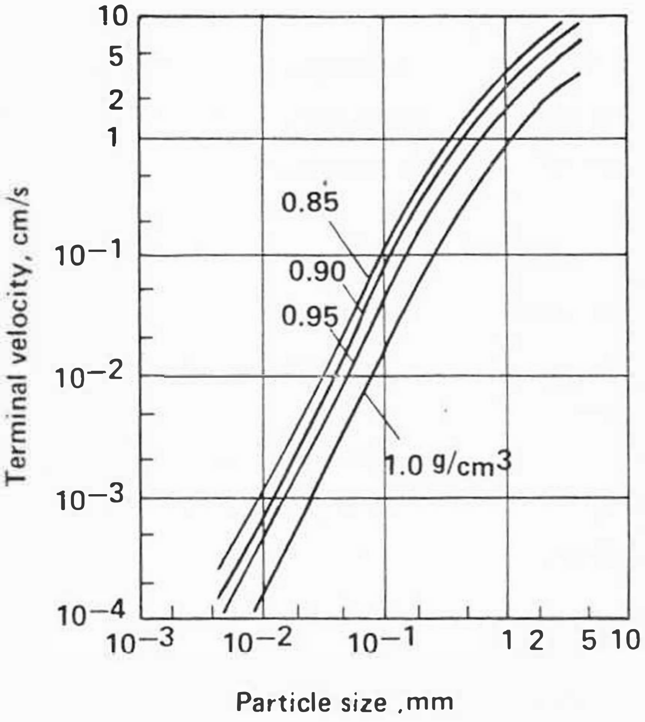


Fig. 10. Terminal velocity of oil particles of of different density in sea water with density 1.025 g/cm^3.

event, it seems to be more reasonable to relate the long term distribution to the combined effect of turbulent diffusion and buoyance. As will be shown in the next paragraph, this is a highly selective mechanism, leading to a rather fast resurfacing of larger droplets, while smaller droplets may be kept in suspension for extensive time.

b) Diffusion-advection model.

On the basis of the previous qualitative description of the dispersion process following a breaking wave, a mathematical model has been chosen which takes into account both aspects of the mixing process. The model predicts the development of the vertical oil concentration profile from an assumed initial profile established immediately after the wave has broken. The further development is governed by the equation:

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial z} \left(D_z \frac{\partial c_i}{\partial z}\right) + w_i \frac{\partial c_i}{\partial z}$$

where D_z is the vertical eddy diffusion coefficient,
w_i, the terminal velocity of the oil droplets of class i
c_i, the oil concentration of particles of class i.

The equation describes the development of the concentration profile for particles of a given size. The resulting concentration from a cloud of droplets with a given size distribution may be found by superposition of the results for each particle class.

In order to obtain realistic results from the model, a number of conditions and parameters have to be established:

- The initial concentration profile
- The initial particle size distribution
- The terminal velocity of oil droplets of various size and density
- The vertical eddy diffusion coefficient

Some of these points have been discussed previously.

With respect to the initial concentration profile, experimental results are available, indicating that this profile may be represented as a linearily decreasing concentration from the surface down to a certain mixing depth (Næss 1981). This mixing depth is observed to be in the order of the height of the breaking wave (Fig.11).

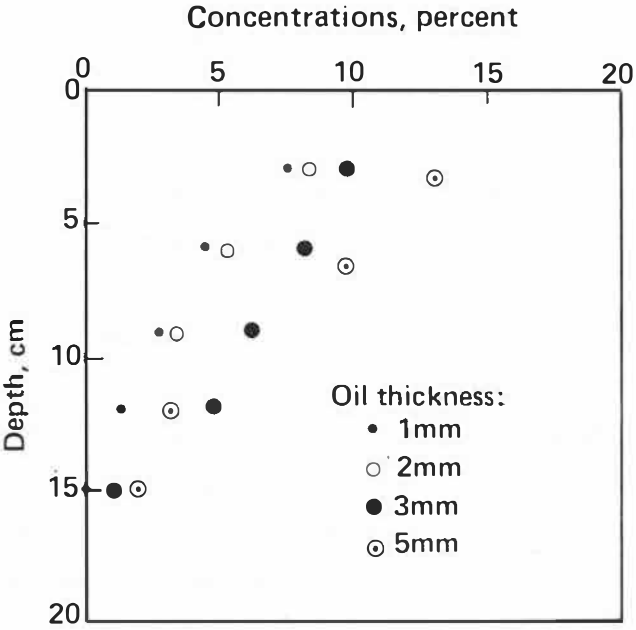


Fig. 11. Initial concentration profiles obtained from experiments with single breaking waves. The wave height was 25 cm in all cases. (Næss 1981).

However, in order to take advantage of this observation one must be able to relate the height of the breaking waves to the sea state, or more preferrably, to the significant wave height, H.

Studies of wave statistics indicates that the breaking waves in general are smaller than the significant wave height (Houmb and Overvik, 1976). For the present purpose one may introduce a reduction factor α which is intended to take into account both this fact and the unscertainity in the relation between the initial mixing depth and the height of the breaking waves. It follows:

$$Z = \alpha H, \text{ where } \alpha < 1$$

As a first estimate, let α be 0.5.

The vertical eddy diffusion coefficient should preferably be expressed in terms of the sea state. Since the initial mixing depth mentioned previously is assumed to be related to the wave height, a model for the eddy diffusion coefficient based on wave parameters has been chosen. The model presented by Ichiye (1967) also describes the vertical variation in the diffusion coefficient:

$$D_z = 0.028 \frac{H^2}{T} e^{-2kz}, \quad m^2/s$$

where H is the significant wave height, m
T, the average wave period, s
k, the wave number
z, depth, m

In order to relate the wave parameters H and T to the sea state, the significant wave height and the wave period have been computed from the wind speed and fetch by the empirical correrelations resulting from the JONSWAP-program (Hasselman 1973). Fig. 12 shows the resulting H and T computed from these equations, while the corresponding eddy diffusion coefficients for depth $z=0$ are shown at fig. 13. The variation of D_z with depth predicted by Ichiy's model is shown at fig. 14 in terms of the relative depth z/H.

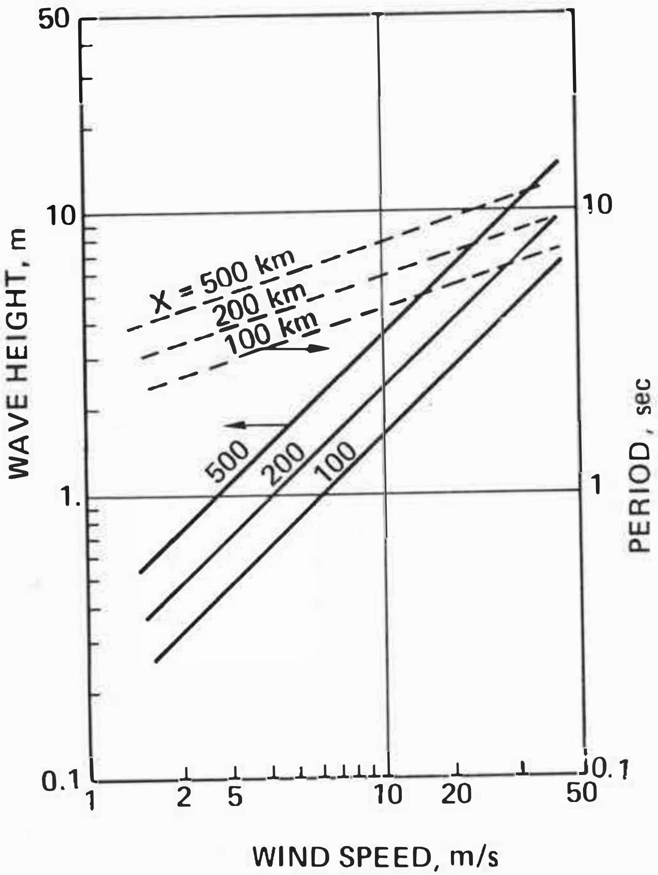


Fig. 12. Wave height and period versus wind speed according to the JONSWAP model.

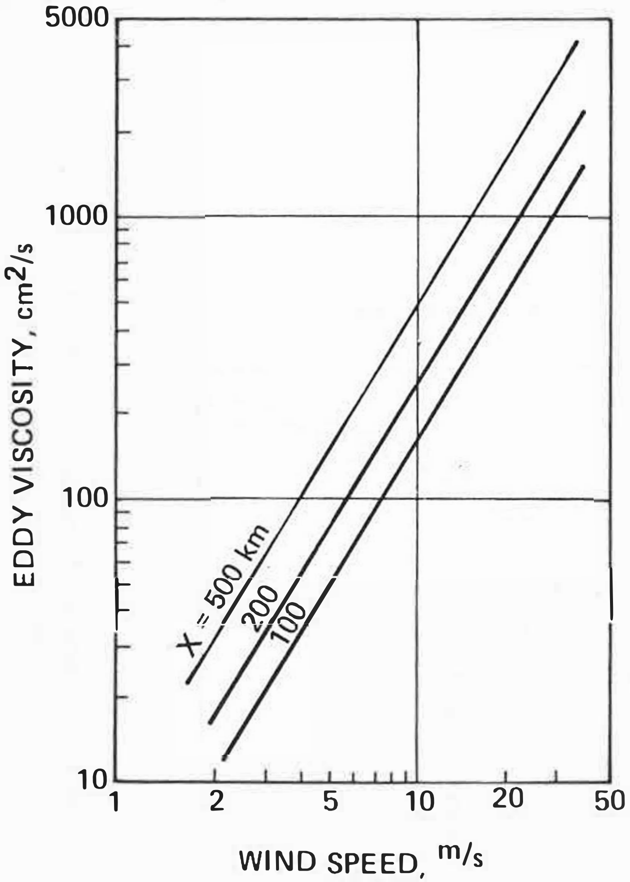


Fig. 13. Eddy viscosity versus wind speed at z=o, based on Ichiye's correlation and JONSWAP waves.

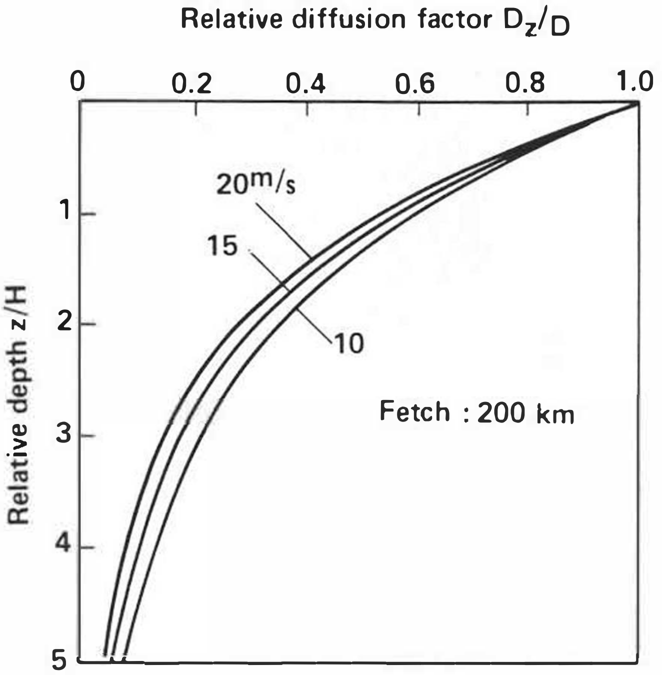


Fig. 14. Variation of the eddy diffusion factor with depth.

The results indicate a relatively small influence of the sea state on the variation with respect to this relative depth. Thus, one might chose a simpler expression for the depth variation:

$$D_z = D\ f(z/H)$$

where $D = 0.028\ H^2/T$,
f(z/H), a functional relationship representing the average of the depth variation shown at fig. 14.

Such a choise may also be convenient with respect to the handling of the diffusion-advection model defined previously. The equation may then be normalized by introducing a set of dimensionless variables:

$\tau = tD/Z^2$, normalized time
$\zeta = z/Z$, normalized depth
$\omega = wZ/D$, normalized terminal velocity
where Z is the initial mixing depth.

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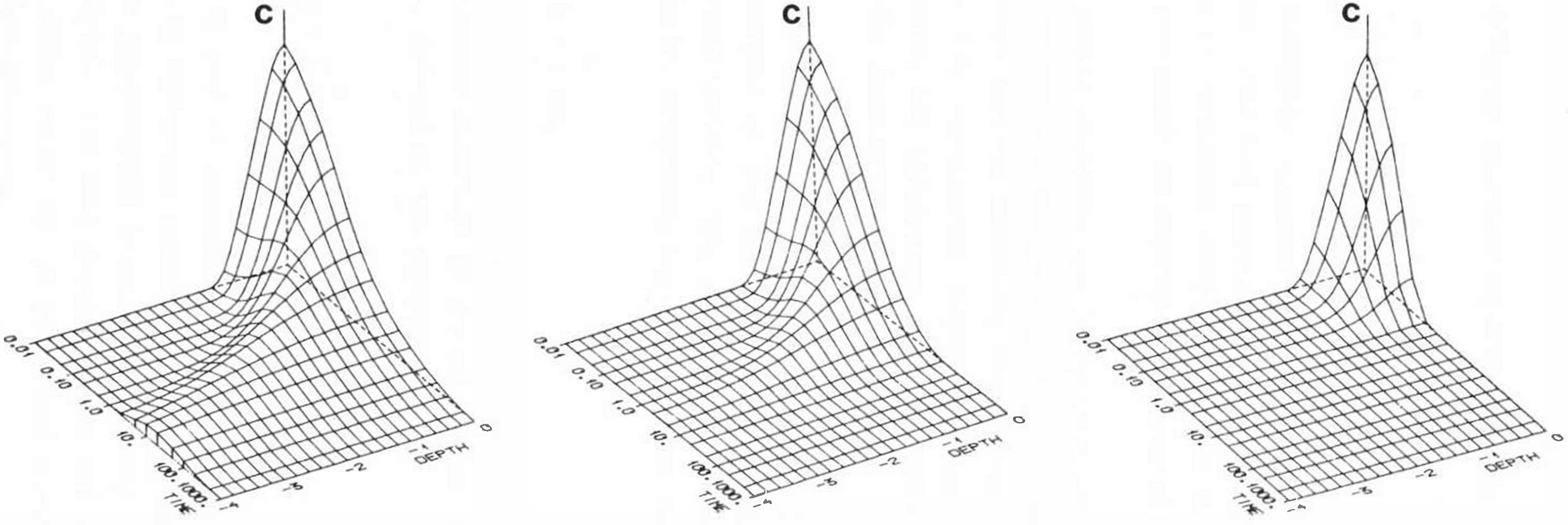


ω = 0.05

ω = 0.5

ω = 5.0

Fig. 15. Time development of the concentration profile for different normalized terminal velocities.

The diffusion-advection equation may then be written:

$$\frac{\partial c}{\partial \tau} = \frac{\partial}{\partial \zeta} \left(f(\zeta) \frac{\partial c}{\partial \zeta}\right) + \omega \frac{\partial c}{\partial \zeta}$$

The normalized equation has been solved numerically by a finite difference method. The time development of the concentration profile for a selected range of normalized terminal velocities is shown at fig. 15. Note that both time and depth are expressed in terms of normalized variables.

The graphs illustrate the changing importance of respectively the process of advection and diffusion as the normalized terminal velocity increases. For small terminal velocities, the dominating process is seen to be diffusion since the penetration depth increases with time. At large terminal velocities, the penetration depth is found to decrease with time, indicating that the dominating process is advection.

In order to evaluate the residence of submerged oil in the sea, the time development of the total volume of submerged oil seems to be the most important variable. The submerged oil volume has been computed from the results by integrating the concentration profile with respect to depth:

$$V = \int_{0}^{\infty} c d\zeta$$

The vertical extension of the oil volume may be expressed by an average depth, defined by the equation

$$\zeta = \frac{1}{V} \int_{0}^{\infty} c\zeta d\zeta$$

Fig. 16 and 17 illustrates the time development of these variables for a range of normalized terminal velocities. Note that the initial submerged oil volume by definition is equal to 1, while the corresponding average depth will be 1/3. The time development of the submerged oil volumes are found to be quite similar for all normalized terminal velocities, differing only by a certain time factor.

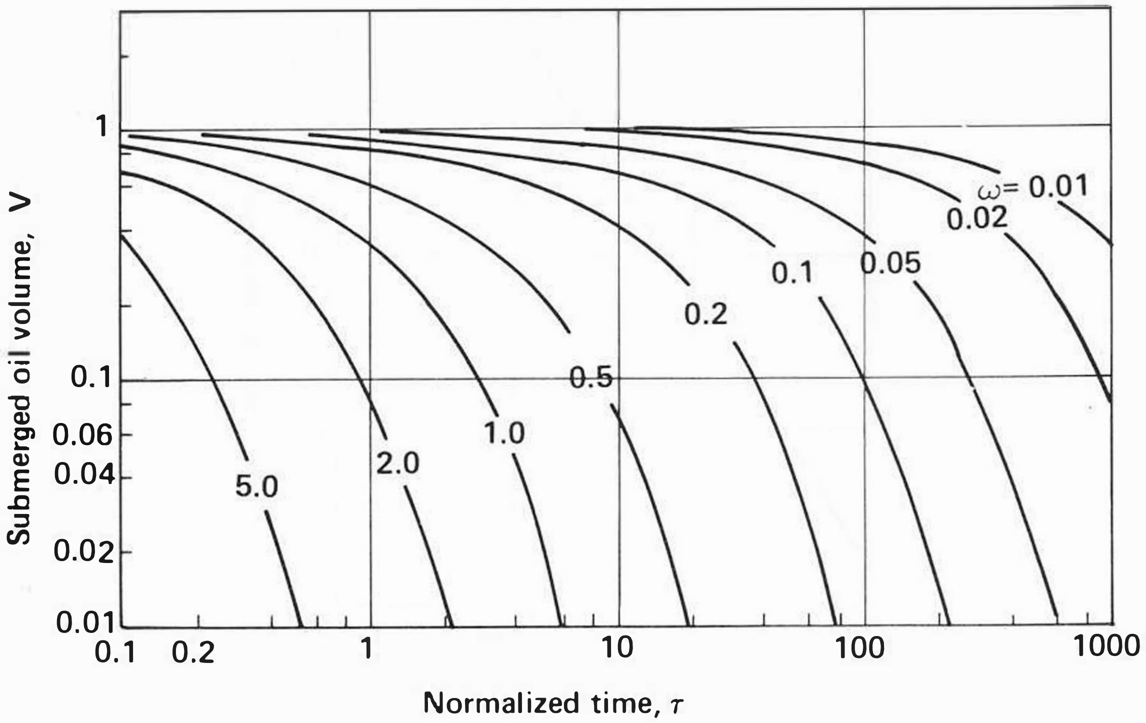


Fig. 16. Time development of submerged oil volume for a set of normalized terminal velocities.

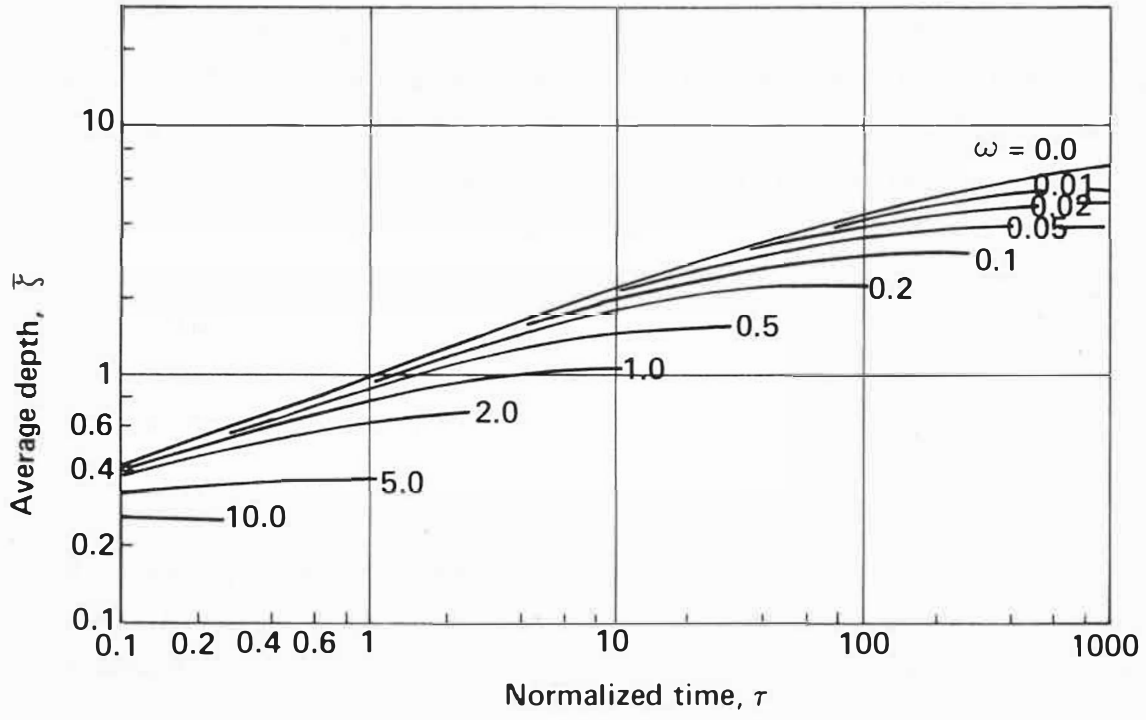


Fig. 17. Time development of normalized average depth for a set of normalized terminal velocities.

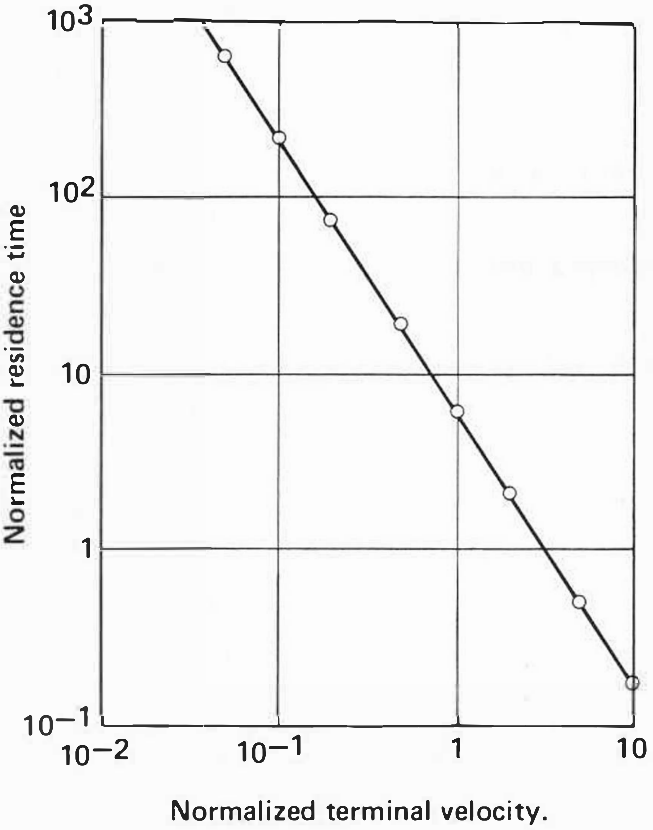


Fig. 18. Residence time of submerged oil versus terminal velocity.

The residence time may be defined as the time elapsed when only a certain small fraction of the initial submerged oil volume is remaining in the sea. For the present purpose, the residence time has been chosen as the time elapsed when only 1% of the oil volume is remaining. The residence time according to this definition is plotted versus the normalized terminal velocity at fig. 18. The plot reveals a simple relationship between the normalized terminal velocity and residence time:

$$\tau^*(\omega) = a\omega^{-\alpha}$$

where $a = 6.0$

$\alpha = 1.55$

By scaling the time variable τ by the residence time τ^*, it has been possible to express the time development of the submerged oil volumes with a single functional relationship valid for all normalized terminal velocities:

$V(t) = f(t/t^*)$

where t^* is the residence time for a given normalized terminal velocity,
t, the time elapsed since the breaking event.

The functional relationship is found to be correlated with acceptable agreement by the function:

$$f(x) = \frac{1}{2} (e^{-\alpha_1 x} + e^{-\alpha_2 x})$$

where $\alpha_1 = 3.912$
$\alpha_2 = 13.04$

Thus, the following procedure has been established for evaluating the time development of the submerged oil volume following a breaking wave event:

- Compute the normalized terminal velocity ω corresponding to the actual particle size and sea state.
- Compute the normalized residence time from the function $\tau^*(\omega)$.
- Compute the submerged oil volume in terms of time by the unified function $f(x)$, with $x = \tau/\tau^*$.

4. ACCUMULATION OF OIL BELOW A DRIFTING OIL SLICK

In the previous chapter, the time development of a submerged oil volume following a breaking wave event has been analysed. In the present chapter, the results from this analysis will be applied to the problem of estimating the residence time for submerged oil mixed into the sea from a drifting oil slick. The following scenario will be considered:

- The oil slick is assumed to have a certain horizontal extension and a certain surface oil concentration, which may be concieved as an average oil film thickness, i.e. oil volume pr. unit area.
- The slick moves with a drift velocity corresponding to the surface current.
- The current velocity below the sea surface deviates from the surface current both with respect to strength and direction.

Our interest is focused on the accumulation of oil in the sea below the slick and the succesive decay of this oil volume after the slick has passed by. As the simplest case one may assume that the slick is moving at the surface with a certain velocity, while the water below is stagnant. In order to get somewhat closer to the actual situation, the variation of the current with depth may be approximated by a two layer representation, namely a surface and a subsurface drift, both expressed in terms of the wind vector (Haug 1981). In the present context, the two approaches makes no difference for the derivation of the solution to problem. Thus, the following arguments will be based on the first and simplest approach.

a) Model of accumulation.

The volume of oil accumulated at a certain point in the sea as an oil slick passes by, may be expressed as the sum of the remaining submerged oil volumes originating from the breaking waves which has influenced the slick at this point. By assuming a constant volume V_o mixed down at each breaking event and a constant period of time Δt between each breaking waves, this may be expressed mathematically by

$$W_n = V_o \sum_{i=o}^{\upsilon} f_{n-i}, \quad \upsilon = \min(n,m)$$

In this expression, f_j is the time development of the submerged oil volume after a single breaking wave:

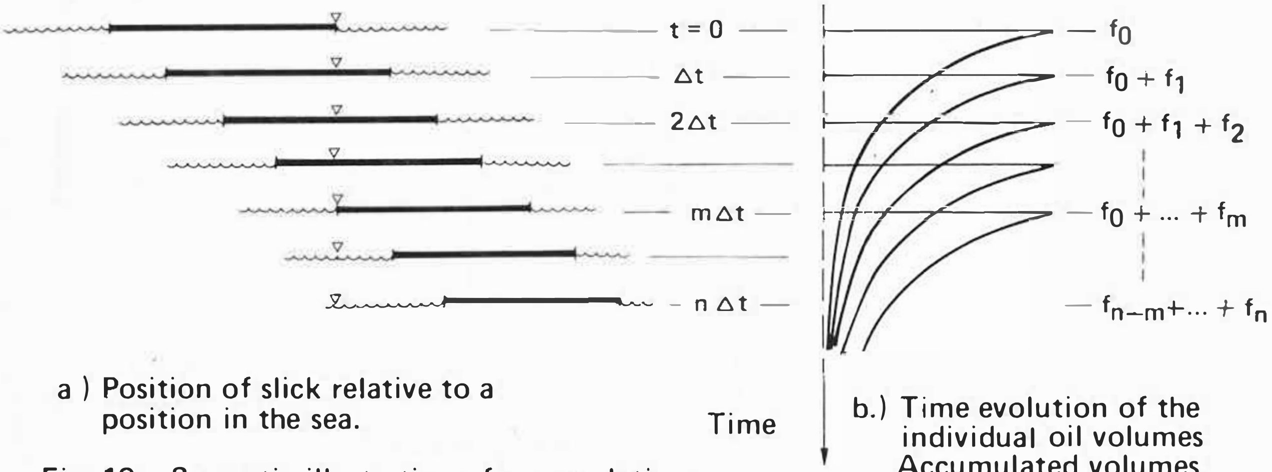
$$f_j = f(j\Delta t)$$

Correspondingly, W_n is the accumulated volume at the time $t_n = n\Delta t$ after the slick has entered the point. The final index υ in the summation is specified as

$$\upsilon = \min(n,m)$$

where the index m corresponds to the time elapsed when the slick has just passed the point, i.e. $t_m = m\Delta t$.

The basis for this expression has been illustrated by fig. 19, showing the position of the slick relative to the given position, the time development of the individual oil volumes mixed down, and the accumulation of oil with time. A similar approach has been applied previously by Fallah and Stark (1976).



a) Position of slick relative to a position in the sea.

b.) Time evolution of the individual oil volumes Accumulated volumes.

Fig. 19. Scematic illustration of accumulation of oil at a position in the sea as an oil slick passed by.

The summation presented above may more conveniently be expressed as an integral:

$$W(t) = \frac{V_o}{\Delta t} \int_{\Theta}^{t} f(\tau)\, dt$$

$$\Theta = \begin{cases} 0; & t < t_m \\ t - t_m; & t > t_m \end{cases}$$

The factor before the integration sign may be concieved as an intrusion rate, V, depending on the frequency of occurence of breaking waves and the volume mixed down by the individual breaking waves. This intrusion rate may be estimated from the relative area covered by breaking wave fronts, i.e. the white cap coverage P_w, and the average wave period T:

$$V = \delta P_w / T$$

where δ is the surface oil concentration, (m^3/m^2)

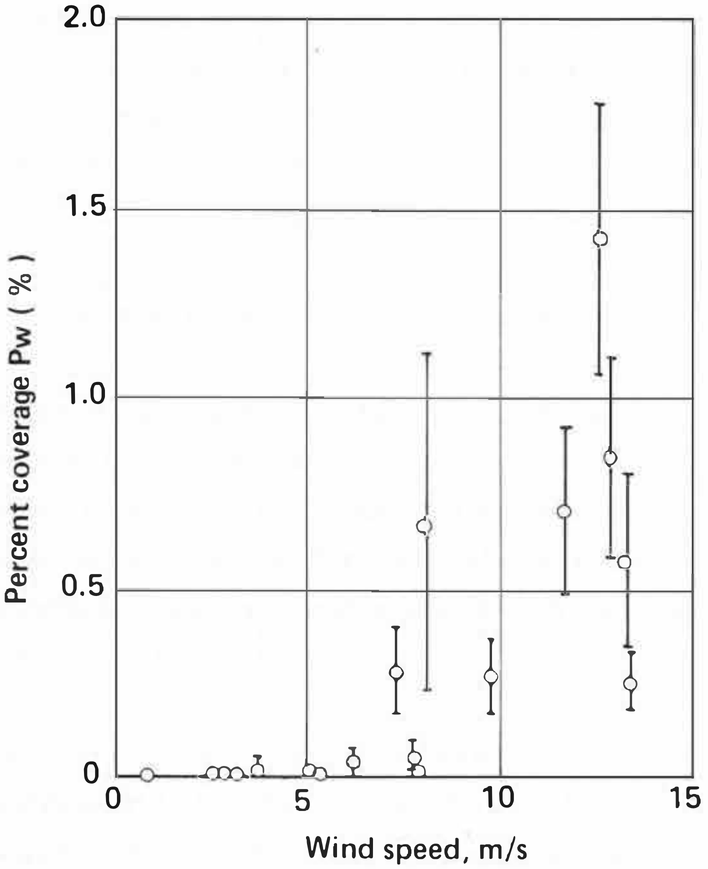


Fig. 20. White cap coverage versus wind speed. A summary of observations from Cardone (1969)

Regarding the coverage of white caps, some relation may be expected to exist versus the sea state. It seems to be generally accepted that white-capping will occure in the open sea as the wind speed increases above 5 to 7 m/s. Above this sea state observations reveals a large spread in the percent coverage. Fig. 20 shows a summary of observations presented by Cardone (1969) as quoted by Shonting et al (1979). For the present purpose, P_w may be expressed by a simple relation

$$P_w = K\ (U-5),\ \text{(percent)}$$

where U is the wind speed, (m/s), and K is an adjustable factor.

The factor K may be chosen in order to fit the upper, medium or lower portion of the spreading shown at fig. 20.

b) Particle size distribution

In the previous analysis, particles of only one size were considered. However, for a real slick, the oil particles mixed into the sea by breaking waves will be distributed over a certain size range. In order to take this into account, one has to assume and initial particle size distribution, defining the volume fraction occupied by particles of each size class, i.e.:

$$V_{o,i} = V_o\ p_i$$

where p_i is the volume fraction of particles of class i.

Regarding the size range of submerged oil, the survey quoted previously seems to indicate a minimum droplet size in the order of 5µm, and a maximum size of 1 to 2 mm. The same survey also reports that the volume distribution as a function of particle size was sensibly constant when averaged over several stations and several depths in the region of particle formation (Forrester 1971).

It should be noted, however, that this average distribution does not correspond to the initial distribution produced by each single breaking wave. The rather sharp increase in residence time with decreasing particle size will certainly lead to an enrichment of the smaller particles in a given volume of the sea as the slick passes by, while the relative fraction of larger particles will diminish due to resurfacing. Based on this argument, one may assume that the initial distribution related to a single breaking wave must be rich in larger particles, while the volume fraction of particles must decrease with decreasing particle size.

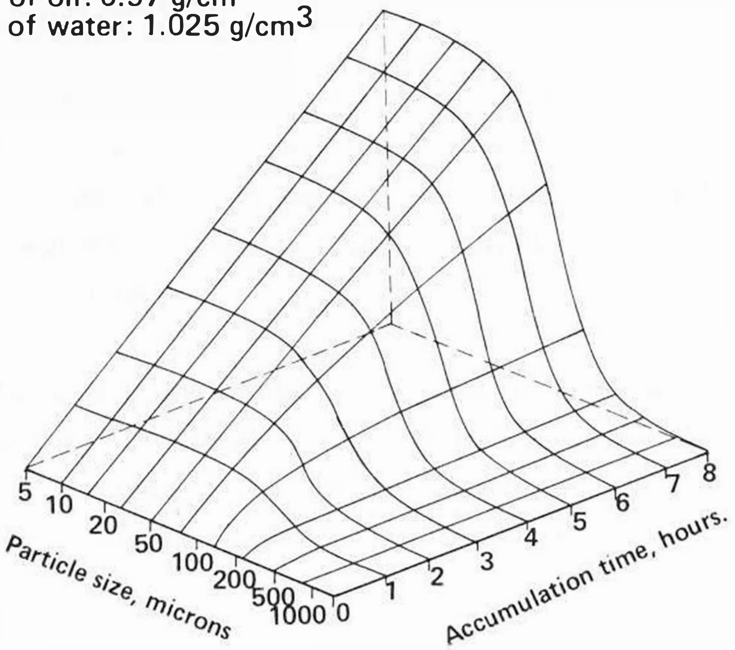
The model derived in the previous paragraph may be used to compute the volume of oil accumulated below a slick for any particle size within the expected range. As an example, a computation has been made for the following conditions:

- Wind speed: 8.5 m/s
- Oil density: 0.97 g/cm^3
- Density of water: 1.025 g/cm^3

The whitecap coverage at the actual wind speed is computed according to the relation

$$P_w = K(U-5), \text{ with } K = 0.1$$

Fig. 21. Accumulated oil volume with time for the expected range of particle size.
Wind speed: 8.5 m/s
Density of oil: 0.97 g/cm^3
Density of water: 1.025 g/cm^3



The accumulated volumes for particle sizes within the expected range are shown in terms of percent of the surface oil concentration at fig. 21. The initial oil volume mixed down by each single breaking wave is assumed to be divided equally on each particle size in this example. The figure illustrates the point made in the previous with respect to the selectiveness of the process of accumulation. The volume of oil accumulated below the slick will be strongly enriched in smaller particles, while the fraction of larger particles will diminish with time.

The example shown in fig. 21 may be used to estimate an initial distribution which corresponds to the average distribution observed in the vicinity of particle formation. Taking the vicinity of particle formation to be the area covered by the slick, the average distribution may be found by integrating the accumulated submerged oil volume along the slick for each particle size. The variation of the accumulated oil volume along the slick corresponds to the variation with respect to time at a given position in the sea as it is passed by the slick. The average volume of submerged oil for any particle size class 'i' may then be expressed as:

$$Q_i = \frac{1}{t_m} \int_o^{t_m} W_i(t)dt$$

where t_m is the time elapsed from the slick enters till it leaves.
W_i, the accumulated submerged oil volume for particle class 'i'.

For given conditions with respect to sea state, Q_i will only depend on the fraction of particles of class 'i'. According to the observations reported by Forrester (1971), Q_i was found to be equal for every particle size. Given this condition, the equation presented above may be used to evaluate the initial particle size distribution.

For the present purpose, the slick length will be chosen as 5 km. The time t_m will then depend on the relative drift velocity between the slick and the point of accumulation. In order to obtain an estimate of the relative drift velocity, the two layer model proposed by Haug (1981) will be used:

- Surface drift: 3.5% of wind speed, turned 15° to the right of the wind.

- Subsurface drift: 1.3% of wind speed, turned 45° to the right.

The relative drift velocity for a wind speed of 8.5 m/s will then amount to 17 cm/s, and the corresponding time t_m will be in the order of 8 hours for a slick size of 5 km.

The initial particle size distribution that fullfills the conditions of a uniform average particle size distribution in the vicinity of particle formation (i.e. over the area covered by the slick), is shown at fig. 22 in terms of a cumulative distribution. As expected, the distribution is found to be dominated by large particles, with as much as 85 percent in the region above 1 mm.

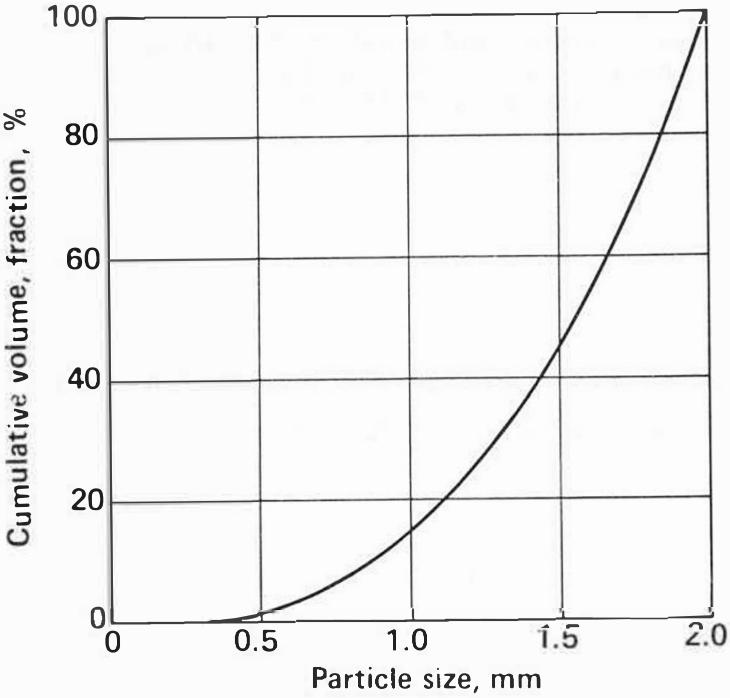


Fig. 22. Cumulative particle size distribution function obtained by assuming a homogeneous average distribution in the vicinity of particle formation.

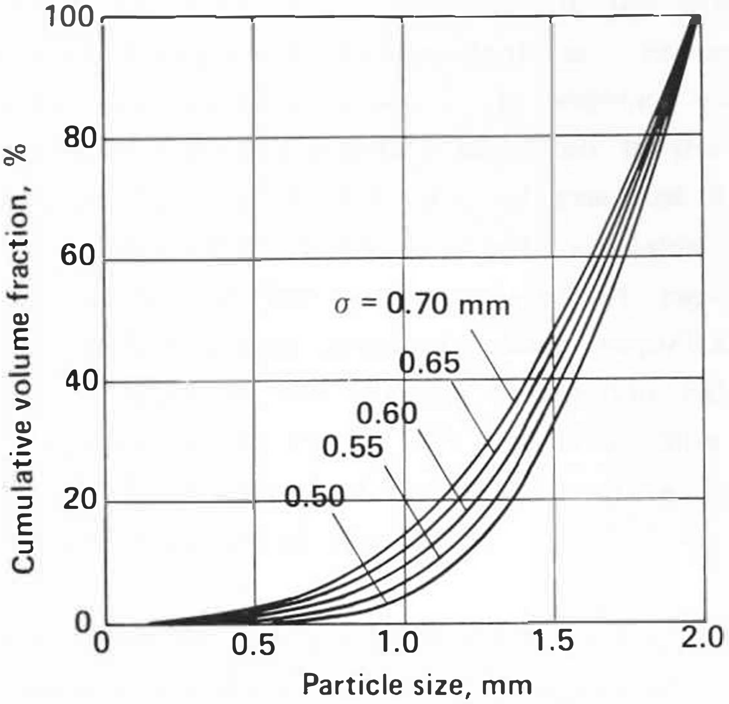


Fig. 23. Cumulative distributions based on the half normal distribution with various values of the scale factor σ

The distribution function obtained in this way is found to be fitted rather well by a half normal distribution with a probability density according to the function:

$$p(x) = \frac{2}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$$

where the expected value μ corresponds to the maximum particle size, x is the actual particle size.

The standard deviation σ represents the scale factor in the distribution. The volume fraction of the smaller particles may be reduced by decreasing the value of σ as indicated at fig. 23.

c) Dissipation rate

Since the model which has been developed in the present report is highly idealized and to a large extent dependent upon rather rough assumptions, there is an obvious need for some kind of empirical evaluation of the model results. The choise of the seastate condition in the previous analysis of the particle size distribution, i.e. a wind speed of 8.5 m/s, was made to make it possible to compare the results with available observations from the Bravo accident, where the average wind is reported to be of this strength. From the Bravo accident, some empirical results have been reported with respect to the average dissipation rate of oil slick due to vertical mixing. Audunson et al (1977) gives a value of 10-15% a day with reference to the total amount of oil at the surface. Converted to fractions pr. hour, this will amount to about 0.5%.

The model derived in the previous analysis may be used to compute a dissipation factor, based on the following argument:

The submerged oil volume below the trailing edge of the slick will correspond to the oil volume accumulated in the sea during the time t_m elapsed from the slick enters till it leaves this certain position in the sea.

Previously, this oil volume has been expressed as $W(t_m)$ relative to the surface oil concentration. By assuming a steady state, it may be argued that the loss rate expressed pr unit width of the slick and unit time will be:

$$w_{loss} = W(t_m)u$$

where u is the drift velocity of the oil slick relative to the sea.

In the time elapsed for the slick to pass by the given position, the total lost volume pr. unit width will be

$$\begin{aligned} W_{loss} &= w_{loss}\, t_m \\ &= W(t_m)\, ut_m \\ &= W(t_m)L \end{aligned}$$

where L is the length of the slick.

The relative loss pr. unit length and unit time will then be:

$$\lambda = W(t_m)/t_m$$

This loss factor is pr. definition equal to the dissipation rate, and may thus be a convenient parameter for evaluation of the model.

The loss factors obtained with the set of parameters defined in the previous paragraph are presented in terms of slick length at fig. 24. The solid line represents the loss factor computed with the initial particle size distribution derived from the assumption of a uniform average distribution. The broken lines correspond to the results obtained from initial distributions according to the half-normal distribution, with various choises of the scale factor σ. Note that the initial volume fraction of the finer particles increases with increasing σ.

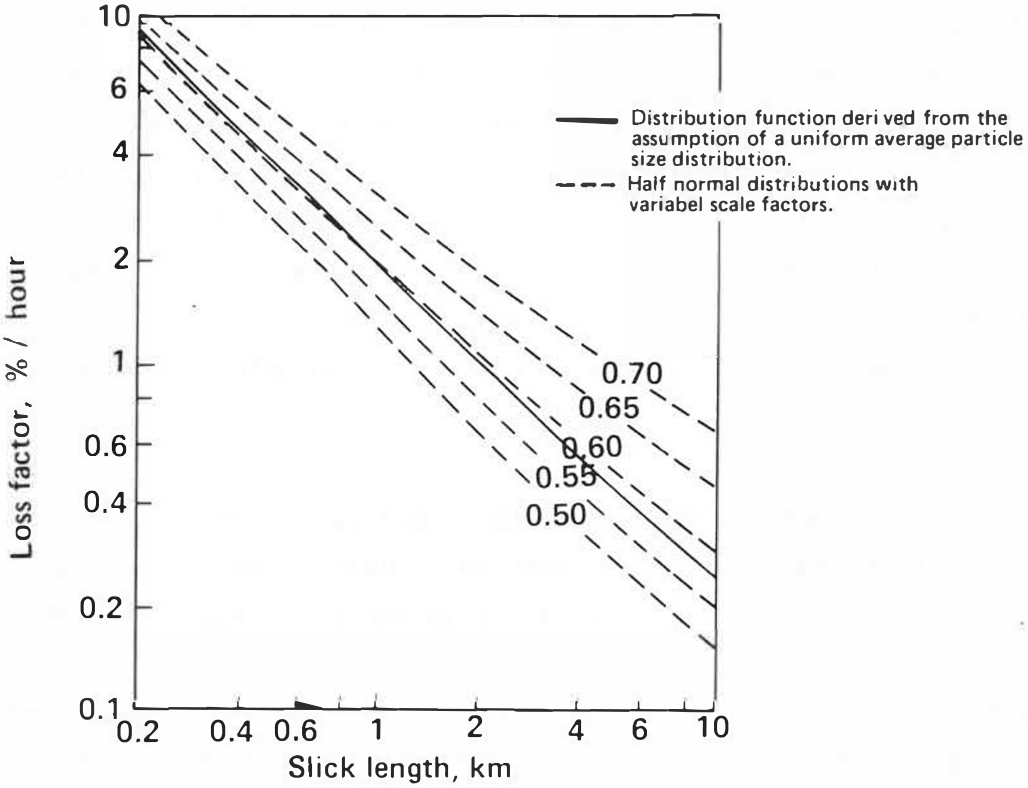


Fig. 24. Computed loss factors at a wind speed of 8.5 m/s for various choises of the initial particle size distribution.

The figure reveals two interesting features:

1. The loss factor is highly sensitive to the horizontal extension of the slick, and decreases almost in proportion to the inverse of the slick length.

2. The loss factor increases with increasing initial volume fraction of the finest particles, corresponding to an increase in the scale factor σ.

Both of these observations may be expected from simple reasoning: As the extension of the slick increases, a larger portion of the dispersed oil may be expected to resurface to the slick, in effect reducing the loss factor. An increase in the fraction of smaller particles will increase the residence time of the dispersed oil, and thus reduce the volume resurfacing within the slick.

The observations from the Bravo accident also includes some information on the extension of the oil slick: The main slick formed in the vicinity of the blowout was found to be splitted in several smaller slicks which where spread over the sea with increasing distance from the platform (Audunson et al 1977). The extension of each of these slicks were found to be quite variable, and not easily defined due to the more or less clear distinction between thick and thin oil appearing at the surface. However, from the maps shown in the report, the size range seems to be in the order of 10 km.

For slicks of this size, the results obtained by the model is actually found to agree reasonably well with the observed average dissipation factors which were reported to be within a range from 0.4 to 0.6 percent an hour.

The scale factor which seems to give the best fit to the observed dissipation factor is in the order of 0.65. The initial particle size distribution corresponding to this scale factor has been shown in cumulative form at fig. 23. The graph shows the volume fraction of particles with size smaller than a given value. It may be noted that this particular distribution is dominated by large particles: About 90% of the volume is occupied by particles in the range from 1 to 2 mm. The large fraction of the larger particles may be taken as a measure of the stage of weathering. As mentioned previously, weathered oil will be present as a highly viscouse water in oil emolusion, which will be more resistant against splitting than fresh oil.

5. SURVIVAL OF SUBMERGED OIL

In the previous chapter, the attention was focused on the accumulation of oil at a fixed position in the sea as it was passed by a drifting oil slick. On this basis, an estimate of the particle size distribution produced by each single breaking wave was established. In this chapter, the evolution with time of the submerged oil volume will be studied from the time the slick leaves the fixed position in the sea, assuming a particle size distribution as derived in the previous paragraph.

a) Time development of submerged oil

From the time the slick leaves a given position in the sea the accumulation of oil will cease and the submerged oil volume will start to decay due to the gradual resurfacing of the oil particles. The evolution with time of the submerged oil volume is shown at fig. 25 for a wind speed of 8.5 m/s, an oil density of 0.97 g/cm^3 and the initial particle size distribution derived in the previous paragraph. The figure reveals that the decay of the submerged oil volume is strongly dependent on the horizontal extension of the slick. Further more, the decay is found to be characterized by a rapid drop in the first few hours after the slick has passed. This drop corresponds to the loss of the larger particles. As time progresses, the remaining oil volume will be dominated by finer particles, and the rate of decay will slow down.

From the details of the computations, it is found that practically all particles larger than 100 microns is lost to the surface after 24 hours. This is illustrated at fig. 26, showing the change in the particle size distribution from the moment the slick has left the position. The extension of the slick in this example is once more taken as 10 km.

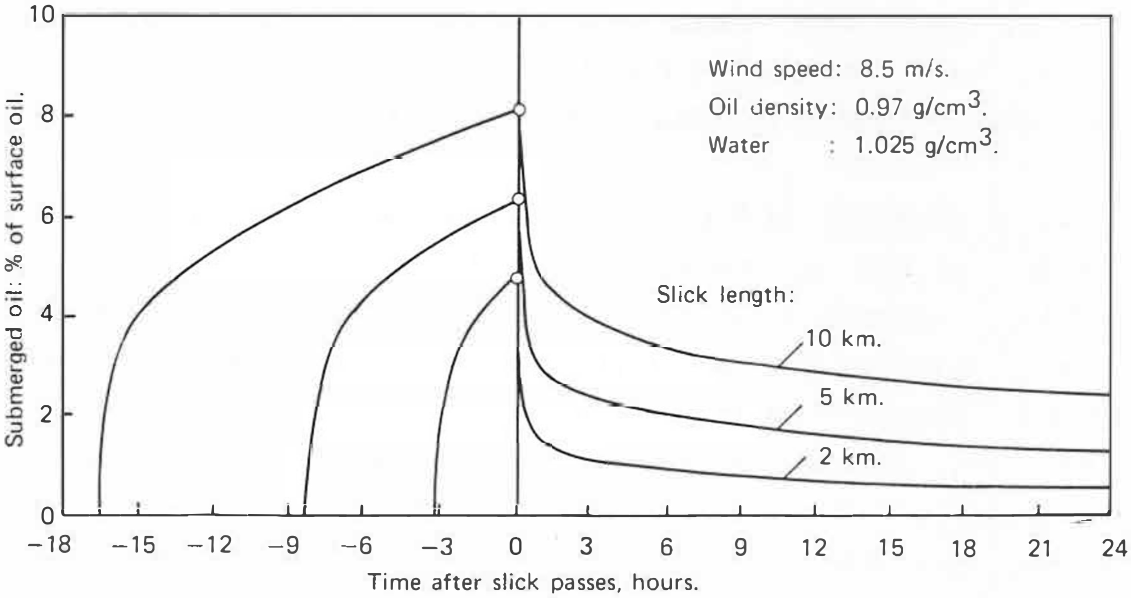


Fig. 25. Evolution with time of the submerged oil volume. The time variable is zero at the time when the slick leaves the point of accumulation.

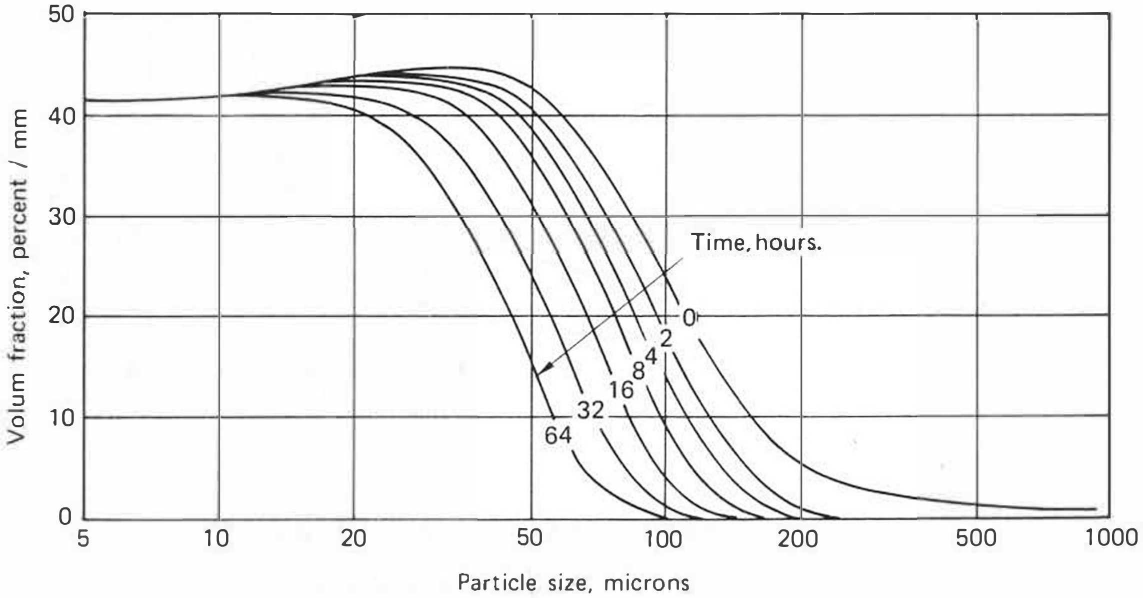


Fig. 26. Time evolution of the particle size distribution after the slick has passed by. Wind speed: 8.5 m/s Slick length: 10 km.

With increasing wind speed, the submerged oil volume remaining in the sea after a certain time may be expected to increase. Several factors contribute to this, such as the increase in the frequency of breaking waves, the wave hight and the level of turbulence. However, the surface drift velocity also increases with wind speed. This implies that the time for accumulation of oil below the slick will be reduced, in effect leading to a larger horizontal spreading of the oil which is dissipated from the slick.

In total, however, the remaining submerged oil volume is found to increase with wind speed, although with a diminishing rate as the wind speed increases. Thus, at moderate to high wind speeds, the effect of the horizontal extension of the slick is found to be more important than the actual wind speed. The results of a set of computations for variable wind speeds and slick lengths are summarized in fig. 27. The contours designate the submerged oil volume remaining in the sea 24 hours after the slick has passed. For the range of wind speeds and slick dimensions covered by the computations, the maximum remaining oil volume is found to be in the order of 5 percent relative to the surface oil concentration in the slick from which the oil originates. As time progresses, this volume will be reduced further.

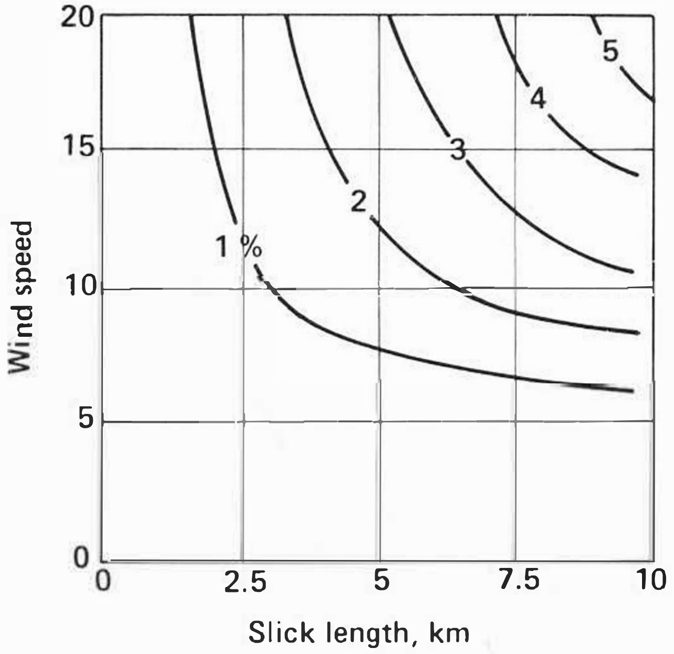


Fig .27. Submerged oil volume after 24 hours. The contours indicate the submerged oil volume relative to the surface oil concentration in the slick from which the submerged oil orginates.

As noted previously, the remaining submerged oil volume will be dominated by the finer particles. The process which tends to keep these particles in suspension, i.e. the process of turbulent diffusion, also tends to dilute the oil volume into the water column by increasing the depth of penetration of the submerged oil cloud. In order to get a measure of this effect, it is necessary to take into account the development with time of the concentration profile. This may be done by the same method as derived for the computation of the accumulation of the submerged volume, i.e. by adding up the response functions for the concentrations at each depth due to succesive breaking waves. Fig. 28 illustrates the time development of the concentration profile obtained by this method for a slick length of 10 km, a wind speed of 8.5 m/s and the same initial particle size distribution and oil density as in the previous examples. Once more, the numbers are expressed relatively to the surface oil concentration in the slick from which the submerged oil originates.

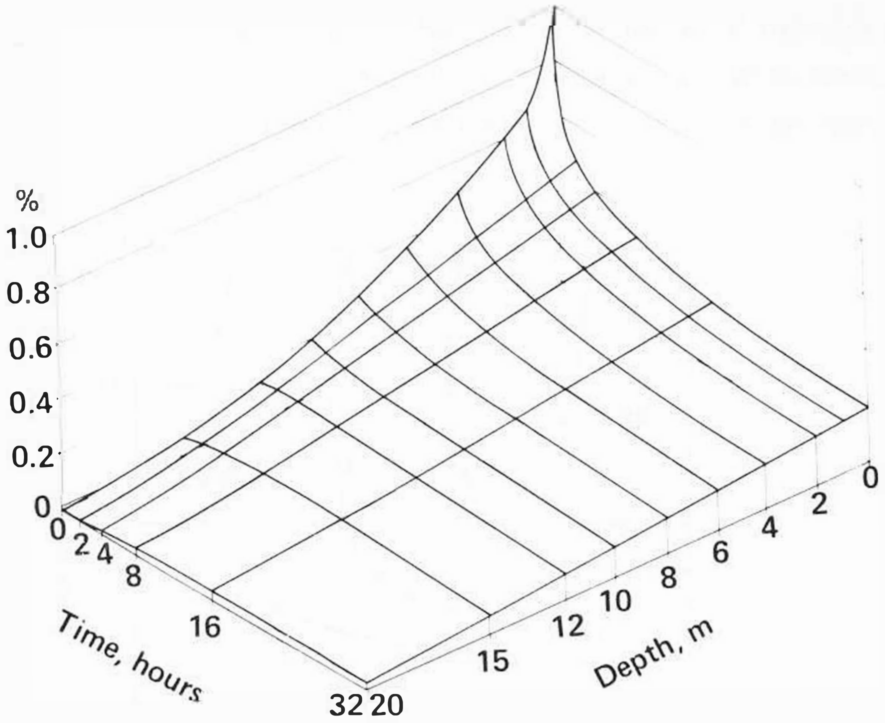


Fig. 28. Time development of the concentration profiles in the submerged oil remaining after a slick of 10 km length. Wind speed 8.5 m/s.

The concentration profiles reveals that the submerged oil volume is effectively diluted in the water column. At the time when the slick just passes by, the oil cloud has penetrated down to a depth of 20 m. As time goes on, the concentration in the near surface region drops off dramatically due to resurfacing of the larger particles, while the concentration at larger depth increases slowly due to the increasing depth of penetration with time for the fine particles.

With increasing wind speed, the effect of dilution of the submerged oil into the water column may be expected to increase. Computations in the range of wind speeds up to 20 m/s in fact show that the oil concentration in the near surface region tends to reach a saturation level at a certain wind speed, followed by a slight decrease as the wind speeds increases further on. Results from a set of computations with variable wind speed and slick dimensions are given at fig. 29. The contours designates the concentration in the upper part of the submerged oil cloud 24 hours after a slick has passed by.

For the range of wind speeds and slick dimensions considered, the maximum concentration is found to be in the order of 2 parts per thousand relative to the surface oil concentration in the slick. With increasing time, the concentration level will be reduced further both due to resurfacing and dilution.

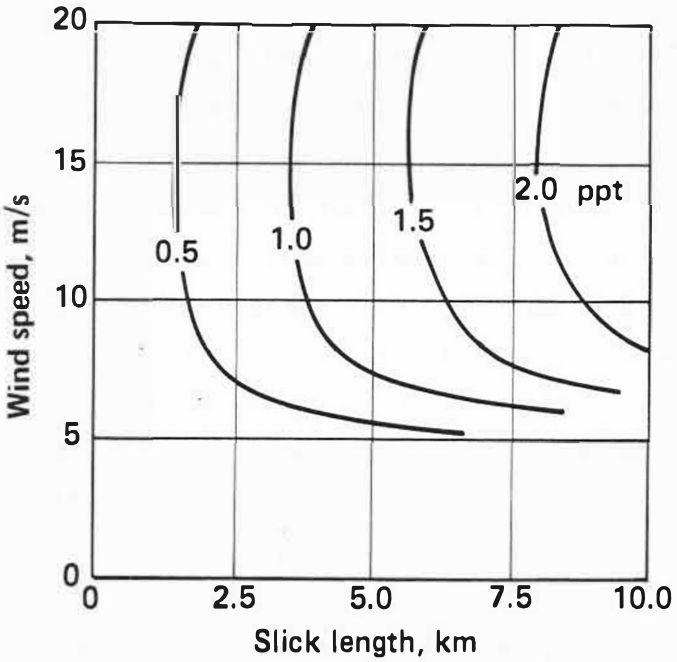


Fig. 29. Near–Surface concentration in remaining submerged oil volume after 24 hours, relative to surface oil contration in slick. (Parts per thousand)

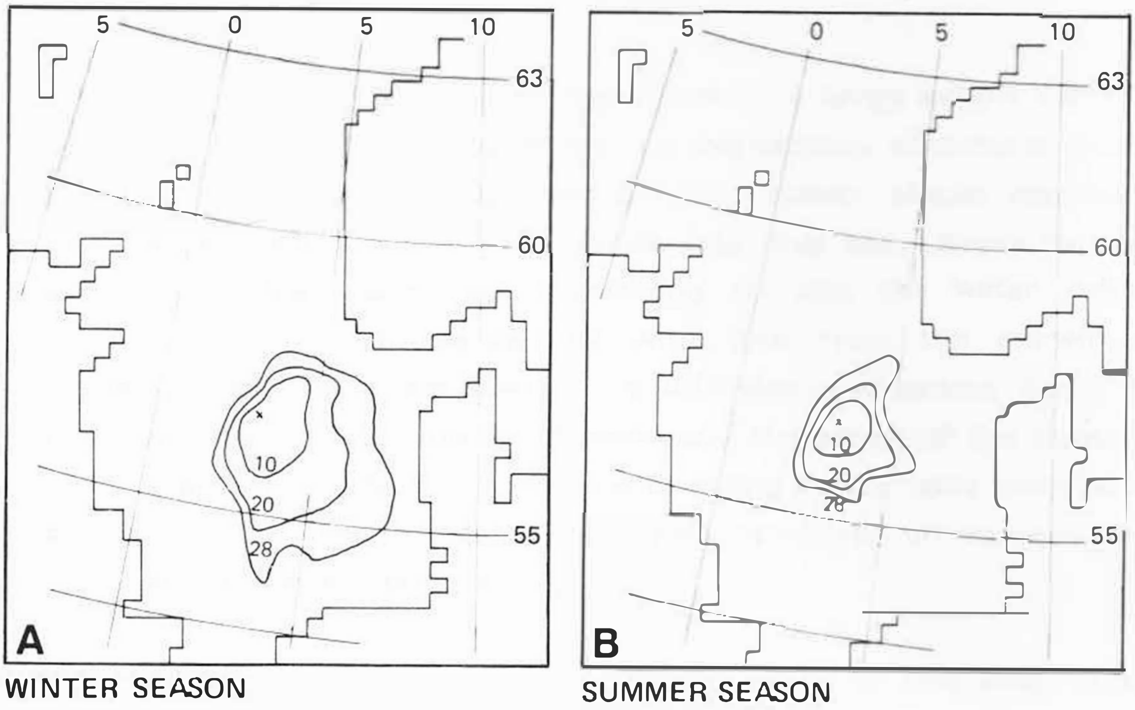
b) The effect of surface concentration

In the previous, the remaining submerged oil volume has been expressed relatively to the surface oil concentration in the slick from which the oil originates. The surface oil concentration is known to depend on the stage of weathering of the oil, i.e. on the time the slick has drifted on the sea. With increasing time, the surface concentration will be reduced due to evaporation, vertical dissipation and horizontal spreading of the oil. In the early stage of the drift, observations from the Bravo accident indicate surface oil concentrations in the order of 100 g/m^2 in the thicker fraction of the slick (Audunson et al 1977). In the later stage of the drift, the surface oil concentration may be assumed to be reduced in proportion to the loss due to evaporation and dissipation. The effect of horizontal spreading will thus be neglected, in effect leading to a conservative estimate of the reduction in the surface oil concentration with time.

The computations of the drift and weathering of oil spilled from Ekofisk, which were presented in the first chapter of this report, may now be used in order to evaluate the magnitude of the submerged oil volume left behind an oil slick, as it is drifting away from the spill site. The reduction in the surface oil with increasing distance from the spill site has been shown at fig. 2 for respectively the winter and summer season, according to the computations reported by Haug and Jensen (1978).

The figure indicates that the surface oil will be reduced by a factor between 10 and 20 at the stage of the drift where the slick is approaching the inlet to Skagerak. With an initial surface oil density of 100 g/m^2, this implies surface oil concentrations less than 10 g/m^2. Within the range of wind speeds and slick extensions considered in the previous analysis, the submerged oil left behind a slick at this stage may be expected to involve less than 0.5 g/m^2 within 24 hours after the slick has passed by. The corresponding concentration level in the upper part of the water column will be less that 20 µg/l (ppb). Thus, submerged oil originating from a slick at this stage of the drift may not be expected to imply any major threat with respect to shore pollution at the coast of Sweden.

Submerged oil remaining from an earlier stage of the drift would have to travel in the sea for an extensive period of time in order to approach the



WINTER SEASON

SUMMER SEASON

Fig. 30. Minimum drift times for dispersed oil relesead at Ekofisk. The oil is assumed to travel at a fixed depth of 5 meters. After Haug et al (1979).

region under consideration. This is demonstrated by the computations of submerged oil drift presented by Haug et al (1979): Fig. 30 shows the minimum drift times obtained for dispersed oil released at Ekofisk in the winter and summer season. The oil is assumed to travel all the distance at a fixed depth of 5 meters. The validity of such an assumption may be questioned, but the results may serve as an indication of the possible spreading of submerged oil originating from positions close to the spill site.

A more realistic computation of the drift and spreading of submerged oil would have to involve a rather comprehensive model which takes into account the mechanismns of dispersion which have been discussed in the present report. The results given in the previous chapter with respect to the behaviour of submerged oil may be seen as a first step in developing a model of this kind. The next step will be to evaluate the results obtained on the basis of an experimental oil spill which will be made in the near future (Sendstad 1982). The future development will be directed towards including the present results into an already existing model for drift and spreading of surface oil (Audunson et al 1980).

6. CONCLUSIONS

The results presented in this report are to a large extent derived on the basis of a recent study regarding the mechanisms of natural dispersion of oil in the sea. The study has led to a rather simple approach to the process by which the oil is mixed into the sea. Breaking waves are assumed to the major factor bringing oil into the water column. The behaviour of the submerged oil with time from the moment of wave breaking has been described by a diffusion - advection model including both the effect of turbulent diffusion and the effect of the buoancy of the oil droplets. The effect of succesive breaking waves have been modelled by adding up the time development of the submerged oil volumes originating from each singel breaking waves.

In order to obtain realistic values from a model of this kind, a number of parameters and conditions have to be established, and several assumptions and simplifications have to be made. Obviously, the validity results obtained will aslo to a large extent rest upon the various choises made during the development of the model parameters. A rather extensive part of the report have been devoted to a discussion of these matters.

A factor which is found to be of major importance is the particle size distribution produced by the breaking waves. Theoretical considerations regarding the splitting of droplets in turbulent flow show that the size of the droplets will depend on the oil properties such as its surface tension and viscosity. This indicate that the particle size distribution will depend on the stage of weathering of the oil. However, the available theory does not lead to any quantitative description of the size distribution. In order to meet the needs for this, data reported from field observations have been used to estimate the particle size distribution. The results obtained by this method has revealed some important aspect of the process of mixing of oil into the sea:

* The oil volume mixed into the sea from the action of each breaking wave will be dominated by large particles (size larger than 1 mm), while the volume fraction of fine particles (size less than 100 microns) is small.

- As oil accumulates below a drifting slick due to succesive wave breaking, the particle size distribution in the submerged oil will change towards a dominance of the finer particles.

- The submerged oil remaining in the sea after the oil slick has passed by will be almost totally made up of fine particles.

This gradual change in the composition of the submerged oil volume is a result of the highly selective processes which determine the behaviour of the oil particles in the sea. For fine particles, the dominanting process will be turbulent diffusion, which tends to keep the particles in suspension. For large particles, the process of major importance will be the buoancy, leading to a rapid resurfacing of the particles.

The rate of dissipation of oil from a drifting slick is found to be strongly dependent on the size distribution in the oil volume mixed into the sea by each breaking wave:

- The amount of oil which is resurfacing within the slick, opposed to the amount of oil left behind, will be strongly dependent on the residence time of the submerged oil.

The horizontal extension of the slick is found to play an important role in the same context:

- With increasing slick length, the part of the submerged oil which is resurfacing within the slick will increase, while the fraction left behind will be reduced in relative terms.

In experimental oil spills, the size of the oil slick will usually be small compared to real oil spills caused by ship groundings or accidents at offshore drilling sites. The last point seems to be an important one in this respect, causing small oil slicks to be broken down within considerably shorter time than slicks of large extension.

The submerged oil volume left behind a drifting slick was found to be dominated by fine particles. The process of turbulent diffusion which tend to keep these particles in suspension is also causing an effective dilution of the submerged oil volume into the water column. For a specific situation, (8.5 m/s wind, slick length 10 km), the depth of penetration of the submerged oil volume was found to be in the order of 20 meters. By increasing wind speed, the penetration depth will increase, and as an effect, the following result is observed:

* At moderate to high wind speeds, the level of concentration in the submerged oil left behind a drifting slick will be retarding rather than increasing with increasing wind speed.

Another factor which contribute to this result is the increase in the drift velocity of the surface oil with increasing wind. In effect, this will lead to a larger horizontal spreading of the submerged oil, which to some extent counteracts the other effects caused by increasing wind, such as a higher frequency of wave breaking, increased turbulence etc.

The general results obtained from the study of the mechanisms of dispersion of oil have been applied to the problem concerning the possibility of shore pollution at the western coast of Sweden due to oil drifting subsea. By combining the results from the present study with computations presented previously regarding the drift and weathering of oil spilled at Ekofisk, the following conclusions could be stated:

* Submerged oil originating from a slick at the stage of weathering expected as it approaches the coast of Sweden will represent a minor threat with respect to shore pollution.

* Submerged oil left behind at an earlier stage of the drift will be efficiently diluted in the water masses before it at any instance can reach the Swedish coast.

A factor which has been given little attention in the context of this report is the development with time of the surface oil. In cases where this is taken into account, the reduction in the surface oil with time is based on results given by established oil drift models. However, the present approach to dispersion of oil might also be extended to account for the time development of the surface oil due to mixing of oil into the sea and succesive resurfacing of the oil either within the slick or behind the slick. The work on a model based on this approach, which tracks both the development of the subsurface oil and the surface oil has been initiated. The results will be presented in a forthcoming report, which is also intended to present an outline of the possibilities for including this model in a large scale oil drift model.

REFERENCES

AUDUNSON, T. 1977: Bravoutblåsningen. Feltobservasjoner, analyseresultater og beregninger tilknyttet oljen på sjøen. Institutt for Kontinentalsokkelundersøkelser, Trondheim. (In Norwegian). 335 pp.

AUDUNSON, T. et al, 1978: Oljesøl langs norskekysten. Institutt for Kontinentalsokkelundersøkelser, Trondheim. (In Norwegian). 174 pp.

AUDUNSON, T. et al, 1980: SLICKFORCAST. Main report. General Description and Discussion of the Simulation Program System. E&P Forum, London. 87 pp.

BOILLAT, J.L. and GRAF, W., 1981: Settling Velocity of Spherical Particles in Calm Water. Journal of the Hydraulics Division. Vol. 107, No. HY10, p 1123-1131.

CARDONE, V.J., 1969: Specification of the Wind Distribution in the Marine Boundary Layer for Wave Forecasting. Geophys. Sci. Lab. TR-69-1- New York University Dept. Meteor. and Oceanogr. 131 pp.

DONS, V., 1977: Beregning av overflatestrøm i Nordsjøen i 1972, på grunnlag av drivkortforsøk. Hovedoppgave i Oseanografi, Geofysisk Institutt. Universitetet i Oslo.

FALLAH, M.H. and STARK, R.M., 1976: A Probabilistic Approach for Dispersion of Oil at Sea. Ocean Engng. Vol. 3. p 145-156.

FORRESTER, W.D., 1971: Distribution of Suspended Oil Particles Following the Grounding of the Tanker Arrow. Journal of Marine Research Vol. 29, No. 1, p 151-170.

HASSELMAN, K. et al, 1973: Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). Deutsche Hydrographische Zeitschrift, Reihe A (8^o), No. 12.

HAUG, O. and JENSEN, O., 1978. Overflatedrift av simulert oljeutslipp på norsk kontinentalsokkel. Klima, nr. 2, s. 3-11.

HAUG, O., JENSEN, O. and WEBER, J., 1979: Drivbaneberegninger for dispergert olje fra boreområder på den norske kontinentalsokkel. Det Norske Meteorologiske Institutt, Oslo. 14 pp.

HAUG, O., 1981: Spreading Oil on Water as an Effect of Wave Influence. "Mechanics of Oil Slicks". Paris. p 189-197.

HINTZE, J.O., 1955: Fundamentals of the Hydro-Dynamic Mechanism of Splitting in Dispersion Processes. A.I.Ch.E. Journal. Vol. 1, No. 3, p 289-295.

HOUMB, O.G. and OVERVIK, T., 1976: Parameterization of Wave Spectra and Long Term Joint Distribution of Wave Height and Period. "Behaviour of Offshore Structures". The Norwegian Institute of Technology, Trondheim. p 144-169.

HU, S. and KINTNER, 1955: The Fall of Single Liquid Drops Through Water. A.I.Ch.E. Journal. Vol. 1, No. 1, p 42-48.

ICHIYE, T., 1967: Upper Ocean Boundary-layer flow determined by dye diffusion. Phys. Fluids Suppl., Vol. 10, p 270-277.

MACKAY, D. and LEINONEN, P.J., 1977: Mathematical Model of the Behaviour of Oil Spills on Water with Natural and Chemical Dispersion. Environmental Impact Control Directorate. Economic and Technical Review Report EPS-3-EC-77-19. 84 pp.

MILGRAM, H.J. et al, 1978: Effects of Oil Slick Properties on the Dispersion of Floating Oil into the Sea. Massachusette Institute of Technology, Cambridge, USA. 326 pp.

NÆSS, A., 1981: On the Residence Time of Oil Mixed into the Water Column by Breaking Waves. 13th Annual OTC, Houston, Texas. Paper 4064.

SENSTAD, E., 1982: Eksperimentelt oljeutslipp, Haltenbanken 1982. Forskningsprogram for Havforurensning. Oslo. 84 pp.

SHONTING, D.H., TEMPLE, P. and ROKLAN, J., 1979: The windwave and Turbulence Observation Program (WAVTOP). Ocean Technology Division. Naval Underwater System Center. Newport. USA. 97 pp.

YALIN, M.S., 1972: Mechanics of Sediment Transport. Pergamon Press. 290 pp.